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Information Compendium on Nonflammable Hydraulic Fluid and Design Requirements for its Adoption

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The purpose of this report is to provide developers of future Army equipment with the information necessary to design systems capable of using a Nonflammable Hydraulic Fluid (NFH) which has a chlorotrifluoroethylene (CFTE) base stock. This hydraulic fluid is described in Air Force draft specification, "MIL-H-XXXX Hydraulic Fluid, Nonflammable, Chlorotrifluoroethylene Base for Aircraft."

The fluid's characteristics and how they will affect the design of the hydraulic system are discussed, along with testing, research data, and conclusions. In addition, system design changes which are required to accommodate this new fluid are suggested. A comprehensive annotated bibliography of the NFH/CTFE development efforts is included.

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SECTION I. INTRODUCTION AND ACRONYMS

The purpose of this report is to provide developers of future Army equipment with the information necessary to design systems capable of using a Nonflammable Hydraulic Fluid (NFH) which has a chlorotrifluoroethylene (CTFE) base stock. This hydraulic fluid is described in an Air Force proposed draft specification, MIL-H-XXXX, " Hydraulic Fluid, Nonflammable, Chlorotrifluoroethylene Base for Aircraft" (see Appendix A).

The fluid's characteristics and how they will affect the design of the hydraulic system are discussed, along with testing, research data, and conclusions. In addition, system design changes which are required to accommodate this new fluid are suggested. A comprehensive annotated bibliography of the NFH/CTFE development efforts is also included in the References section at the end.

The following acronyms and military specifications are used throughout this report.

ACRONYMS

AFES	*See* EAFES
BAD	Behind Armor Debris
BUNA N	Butadiene-acrylonitrile copolymers, nitrile seals
CTFE	Chlorotrifluoroethylene
CMV	Combat Mobility Vehicle, one of the variants of the HFM
EAFES	Enhanced Automatic Fire Extinguisher System
EPDM	Ethylene propylene rubber
FAE	Fluoroalkylether (hydraulic fluid candidate)
FKM	Vinylidene fluoride/tetrafluorethylene/perfluoro (methyl vinyl ether) elastomer
HEIT	High Explosive Incendiary Tracer (ammunition)
HFM	Heavy Forces Modernization
MERADCOM	Mobility Equipment Research and Development Command
MSDS	Material Safety Data Sheet
NFH	Nonflammable Hydraulic Fluid
NHPSTA	Nonflammable Hydraulic Power Systems for Tactical Aircraft
PNF	Phosphonitrilic fluorelastomer
RFP	Request for Proposals
VITON	Vinylidene fluoride-hexafluoropropylene copolymer, elastomer
WPAFB	Wright Patterson Air Force Base

MILITARY SPECIFICATIONS

MIL-H-5606	Hydraulic Fluid, Petroleum Base; Aircraft, Missile, and Ordnance (OHA)
MIL-H-6083	Hydraulic Fluid, Petroleum Base, for Preservation and Operation (OHT)
MIL-H-46170	Hydraulic Fluid, Rust Inhibited, Fire Resistant, Synthetic Hydrocarbon Base (FRH)
MIL-H-83282	Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base, Aircraft, Metric, NATO Code Number H-537

SECTION II. BACKGROUND

Before 1974, the standard operational fluid for all Army ground equipment, including armored vehicles, was MIL-H-6083 (OHT) hydraulic fluid. This somewhat flammable fluid was identified as contributing to loss of equipment and life during the Arab/Israeli conflict of 1973. Consequently, MIL-H-46170 (FRH) was developed and introduced as an interim solution to reduce hydraulic fluid fire threat to armored vehicles.

Since fire risks were still present with FRH (intended to be an interim fluid), the Belvoir Research, Development, and Engineering (RD&E) Center (formerly the Mobility Equipment Research and Development Command (MERADCOM)) initiated a program in 1978 to develop a completely nonflammable hydraulic fluid (NFH). The primary objective of the Army NFH research program was to reduce or eliminate the fire threat to armored vehicles with little or no changes to the system hardware while still meeting all operational requirements. This meant developing a completely nonflammable hydraulic fluid which would be compatible with the elastomers, materials, and metallurgy currently used in hydraulic systems of armored equipment.

The Air Force, with research efforts centered at Wright Patterson Air Force Base (WPAFB), independently of the Army, was also pursuing a program to develop a nonflammable hydraulic fluid for use in aircraft hydraulic systems. After initial research was conducted, it was concluded that a completely nonflammable hydraulic fluid would have to be chemically different from the currently used fluids, MIL-H-5606 (OHA) and MIL-H-83282. Since current aircraft hydraulic system elastomers and component hardware response were designed around the properties of hydrocarbon base oils, it was concluded that a simple retrofit (a one-for-one changeover) with existing aircraft systems was not feasible. Therefore, a program for development of a nonflammable hydraulic fluid without constraints was initiated. A totally new hydraulic system, including all components and compatible elastomeric seals, was to be designed around a nonflammable hydraulic fluid.[1]

To determine the type of nonflammable fluid to replace the existing hydraulic fluids, extensive flammability tests were conducted with a number of candidate fluids selected from several classes of materials (phosphate esters, silicones, chlorofluorocarbons, fluoroalkylethers).[2] Both the Army and Air Force determined that chlorotrifluoroethylene (CTFE) and fluoroalkylether (FAE) base fluids were the final candidates for a nonflammable hydraulic fluid (NFH). All other fluids tested exhibited only a moderately improved reduction in flammability compared to FRH. The final selection of CTFE over FAE for the NFH base fluid was determined because of its cost, availability, and better additive solubility, density, and compressibility.

CTFE fluids are saturated low molecular weight polymers of CTFE with the general formula, $(CF_2CFCl)_n$. Their chemical and physical properties are quite different from the hydrocarbon hydraulic fluids which are used in present military hydraulic systems. The most noticeable problems to overcome in using a CTFE hydraulic fluid were its high specific gravity, high volatility, incompatibility with conventional elastomers, lower bulk modulus (greater compressibility), and the extraordinarily low solubility of additives needed for corrosion inhibition and wear protection.

It was found that the high specific gravity, or density, of CTFE which, at $1.8 g/cm^3$ is approximately double that of the conventional fluids, i.e., OHT or FRH, could not be lowered without compromising the viscosity-temperature properties, volatility, elastomer compatibility, and inertness of the fluid.[1] Therefore, hydraulic system modifications are necessary to compensate for the additional fluid density.

Initial testing of CTFE determined that additives would be required to improve the antiwear properties (lubricity) and to provide protection against rusting. The Army's original approach was to use suitable additives in petroleum base carrier fluids. This was reinforced by the requirement for compatibility with existing systems which use petroleum base fluids and by the discovery that mixtures of CTFE containing up to 20% by weight of FRH and OHT remained nonflammable. Initial research concluded that it was possible to formulate a fluid suitable for retrofit in existing armored equipment.[3] However, it eventually became evident that it was impossible to formulate an NFH compatible with existing elastomers. It was realized that implementation of a CTFE retrofit in existing hydraulic systems would require replacement of essentially all elastomers due to incompatibility, as well as hardware modifications to accommodate the high specific gravity of the fluid. With those modifications, a simple retrofit of the type desired would be more expensive than the cost of an improved fire suppression system.

At that time,the Air Force had already succeeded in formulating a corrosion and wear inhibited fluid that appeared satisfactory for Army applications. Therefore, in 1985, this Center formally coordinated its nonflammable hydraulic fluid with WPAFB who made their latest formulation available to the Army for testing.

The NFH development effort has continued with the goal of implementing NFH in the Heavy Force Modernization (HFM) Program. This effort was reinforced by the 1988 requirement for the availability and use of nonflammable hydraulic fluid, stated by the AirLand Battle-Future-Special Study Group at Ft. Leavenworth, KS.

WPAFB is engaged in a continuing program[4,5,6] with CTFE including:

- Study of the telomerization process of CTFE compounds
- Correlations between structure and properties of CTFE
- Traction testing with CTFE and other hydraulic fluids
- Formulation of non-proprietary additives
- Characterization and evaluations of synthesized base stocks and formulated fluids
- Formulation of improved elastomers for use with CTFE, including improvements of the Viton GLT elastomer
- Development work on a high temperature (350°F) and high pressure (8,000 psi) CTFE base NFH.

The following sections describe physical, chemical, and component testing accomplishments and results. The following table compares properties of CTFE with FRH and OHT. The major problems initially associated with use of CTFE as the base fluid for an NFH (high density, volatility, elastomer compatibility, compressibility, additive solubility) have been resolved.

COMPARISON OF HYDRAULIC FLUID PROPERTIES

CHARACTERISTIC	MIL-H-6083	MIL-H-46170	NFH
Viscosity, cSt:			
@ –54°C (max)	3,500	13,000*	1,200
@ –40°C (max)	800	2,600	NR
@ 40°C	13, min	19.5, max	2.9 (38°C)
@ 100°C (min)	4.3*	3.4	NR
@ 135°C (min)	NR	2.1*	0.60
Pour Point, °C (max)	–59	–54	–60
Specific Gravity	0.86*	0.85*	1.7
Bulk Modulus (psi) (min)	210,000	200,000	176,000
Water %, (max)	0.05	0.05	0.02
Total acid number, (max)	0.20	0.20	0.60
Evaporation Loss, % (max)	70.0	5.0	NR
Vapor Pressure at 121°C, torr (max)	NR	NR	100
Oxidation corrosion test**	pass	pass	pass
Copper Corrosion (max)	3a	NR	3a
Foaming Characteristics			
24°C, 5 min, vol, ml	65	65	65
after 10 min, vol, ml	0	0	0
Swelling of synthetic rubber***, %	19.0 - 28.0	15.0 - 25.0	25.0 - 40.0
Lubricity, wear scar diameter, mm (max):			
10 kg load	NR	0.30	NR
40 kg load	1.0	0.65	0.8
Flash point, °C (min)	82	218	none
Fire point, °C (min)	NR	246	none
Autoignition temp., °C (min)	226*	343	646*
High Temp, High Pressure Spray Ignition	fail*	pass	pass*
Atomized Spray, Open Flame	sustains*	sustains*	non reactive*
Heat of combustion, Kcal/kg, (max)	4,536*	4,284*	2,750
Hot Manifold Ignition			
stream °C, (min)	482*	315*	925
spray °C	760*	704*	<925*
Ballistic Test (20mm) HEIT	mist fireball,* residual burning	mist fireball*	no ignition

Values given are specification requirements unless noted as "typical values" (*)

NR = Not Required; HEIT = High Explosive Incendiary Tracer

* Typical values.

** Federal Test Method Standard 791C, Method 5308. MIL-H-6083 and MIL-H-46170 are tested at 121°C; NFH is tested at 135°C.

*** MIL-H-6083 and MIL-H-46170 are tested with NBR-L rubber; CTFE is tested with Viton A-GLT.

SECTION III. PHYSICAL/CHEMICAL PROPERTIES AND TESTING

FLAMMABILITY

The search for a nonflammable hydraulic fluid (NFH) required a satisfactory definition of hydraulic fluid flammability and relevant tests for determining the relative flammability of various hydraulic fluids under different threats. A 1977 Army study defined the flammability hazards associated with hydraulic fluid systems in Army combat vehicles.[7] Since hydraulic fluid flammability is a very complex hazard, it was recommended that priorities be assigned to various flammability properties relative to specific applications. A comparison of hydraulic fluid flammability characteristics with an overall vulnerability rating was developed in 1982.[8] According to this merit rating scheme, the CTFE and fluoroalkylether (FAE)-base fluids received the maximum rating of 100, while OHT received 32 and FRH received 49.

As a response to the need for a more severe flammability test which more nearly duplicates real world hazards, the Army developed a relatively inexpensive ballistic test procedure which employs 20mm high explosive incendiary tracer (HEIT) projectiles fired into partly filled fluid containers under pressure.[9] The results with the CTFE fluid were similar to those obtained with water. Other flammability tests studied by the Army were mist flammability, with the objective of developing a standardized test procedure,[10] the effect of droplet size on hot surface ignition, and flame propagation.[11] In all tests, the performance of CTFE and FAE was superior to all other hydraulic fluids.

The Air Force was also studying flammability characteristics of aerospace hydraulic fluids and flammability test methods.[12] In comparative testing of flash point, fire point, autogenous ignition temperature, stream hot manifold ignition temperature, gunfire resistance, and horizontal flame propagation, the CTFE and FAE fluids demonstrated such improved fire resistance that they were termed nonflammable hydraulic fluids. A new test method for measuring flame/fire propagation was developed.

The Air Force established flammability requirements for a nonflammable aerospace hydraulic fluid which included testing for heat of combustion, hot manifold ignition, and an atomized fluid flammability test.[13] They established two criteria:

A — all anticipated fire threats
B — all fire threats excluding over-heated carbon brakes from an emergency rejected takeoff.

The hot manifold test method (Federal Test Method 6053 of Federal Standard 791) had to be modified to accommodate the higher temperature limit of 1,700°F required for the NFH.[2]

Flammability under dynamic conditions (the effect of air flow on hot surface ignition) was studied at San Jose State University showing CTFE superior to other fluids.[2]

Since most non-combat aircraft hydraulic fluid fires are initiated by hot brakes in the landing gear/wheel well areas, a two-fluid hydraulic system utilizing NFH in the brake system was developed for and tested in the C/KC 135 aircraft with no significant differences in performance compared to the one-fluid (MIL-H-5606) system.[14,15]

Testing of thin steel overlays to protect hydraulic lines from behind armor debris (BAD) and fire suppression materials to prevent ignition of FRH fluid was performed by the Army Ballistic Research Laboratory in 1985.[16] It was found that hot pressurized FRH fluid escaping from perforated lines readily ignited, providing additional incentive to reconsider replacing FRH with NFH.

VOLATILITY (EVAPORATION)

The volatility of CTFE is also a characteristic of the base fluid which cannot be changed with additives. The concern over high volatility was satisfactorily resolved by conducting a study of the evaporation loss of CTFE in an M60 hydraulic system reservoir, which is essentially a closed system.[17] Evaporation loss was almost identical to the loss for OHT, and negligible for both. Therefore, volatility can be eliminated as a potential problem in the use of CTFE base hydraulic fluids in the hydraulic systems of M60 tanks or similar systems. The Air Force design guide for use with CTFE presents the vapor pressure of CTFE and MIL-H-5606 at various temperatures.[18]

CORROSION AND WEAR (ADDITIVE DEVELOPMENT)

Initial testing of CTFE revealed that antiwear and anticorrosion additives would be needed; however, it was difficult to find an effective, soluble, and thermally stable additive.

In 1985, WPAFB reported that a successful NFH formulation had been achieved utilizing a CTFE oligimer manufactured by the Halocarbon Products Corporation, a 3M Corporation proprietary lubricity additive, and a barium sulfonate rust inhibitor.[1]

A study to determine the wear and corrosion properties of this formulated NFH revealed that the antiwear and anticorrosion additives improved the performance of the NFH over the CTFE base fluid and performed comparably to the FRH.[19]

Air Force-sponsored research is continuing investigation of the synthesis of improved antiwear and antirust additives needed for the NFH to eventually eliminate the proprietary additive which is now required.[6]

ELASTOMERS

An initial major concern with the use of CTFE as the base fluid for an NFH was the lack of compatibility with many seals currently used. This was complicated by the fact that the hydraulic systems of current armored vehicles contain up to seven different elastomers, making it impossible to design a formulation compatible with all elastomers and yielding satisfactory swell, and tensile and elongation retention.

Extensive screening of elastomers was reported by WPAFB,[2] with the phosphonitrilic flourelastomer (PNF) elastomer as the viable candidate for use with CTFE in 1982. In 1985, the Air Force reported that, except for excessive swelling at high temperatures, ethylene propylene rubber (EPDM) and PNF seals met or exceeded target properties. In addition, FKM seals base on vinylidene fluoride/tetrafluorethylene/perfluoro (methyl vinyl ether), or Viton GLT (vinylidene fluoride-hexafluoropropylene copolymer), fluorosilicone seals, and an EPDM/PNF blend demonstrated excellent promise as elastomers for CTFE base hydraulic fluids.[1,20] Continued R&D efforts for CTFE compatible elastomers have demonstrated the leading candidate for high-temperature performance sealing with CTFE to be Viton GLT, although high swelling still remains a problem.[4,5,6] Fluorosilicone and butyl rubber have been investigated as additional possibilities with butyl eliminated because of its incompatibility with CTFE. Fluorosilicone compounds display the best compatibility with CTFE with promising improvements in physical properties being seen.

More complex sealing systems have shown much greater success than simple O-ring and washer systems in Air Force dynamic sealing tests.[21] These designs have a compounded Teflon plastic element bearing on the active surface with a compounded Viton GLT or metal spring energizing element. A high modulus (PEEK) element is used as an anti-extrusion barrier.

The Air Force proposed draft specification for NFH (Appendix A) requires compatibility with the fluorocarbon elastomer, Viton A-GLT, described in MIL-R-83485. A 1987 Army elastomer compatibility study[22] determined that the nitrile seals (Buna N or butadiene-acrylonitrile copolymers) currently used in the hydraulic systems of armored vehicles are not compatible with CTFE. In addition, an antisynergistic effect was observed between CTFE and certain elastomers in the presence of copper and copper alloys, which reinforces the need for material changes in current systems to accommodate NFH. This elastomer compatibility study succeeded in identifying a commercially available compound (the EPDM seal GT-818, supplied by Greene Tweed) and an in-house formulation which are compatible with CTFE and with the formulated NFH.

BULK MODULUS (COMPRESSIBILITY)

A CTFE hydraulic fluid has an isothermal secant bulk modulus value of 12.1×10^8 pascals (176,000 psi) compared to 14.5×10^8 pascals (210,000 psi) for MIL-H-5606 at 3,000 psi. The major potential penalty of a system using a fluid with poor bulk modulus is the requirement for larger lines and increased actuator cross section, hence more weight.[13] This weight penalty can be largely overcome by greater system pressure, which creates a requirement for higher pressure systems. Because of this, 8,000 psi system research was begun.

The high pressure research is discussed in more detail on page 10.

SECTION IV. COMPONENT/SYSTEMS TESTING

M1 WEAPON AND TURRET CONTROL SYSTEM

Since research was initially conducted with retrofitting existing systems in mind, the impact of the less than desirable characteristics of the fluid on existing systems was addressed first. An investigation conducted by Cadillac Gage in 1985 on the M60A3's gun and turret control hydraulic system concluded that minor hardware modifications (modification of the electronics to increase the electrical loop gain to compensate for the decrease in pilot valve flow gain and increase of the flow area of the third stage valve) were required to counter the adverse effects of the high specific gravity of the new fluid.[23]

In 1988, Cadillac Gage completed follow-on testing of NFH in an M1 gun and turret control system modified according to the recommendations of their earlier study.[24] At medium and high temperatures, the performance of the NFH in the modified system was satisfactory and comparable to the performance of FRH in the unchanged system. At low temperatures, NFH demonstrated a much improved performance over FRH. Therefore, with NFH, the heaters used in the M1 to improve FRH low temperature performance could be removed. Base upon the success of this testing, Cadillac Gage recommended the modification and further testing of M1 vehicles for a possible NFH retrofit.

GUN MOUNTS

The CTFE base fluid has also been tested in two gun mounts. In 1984, CTFE was tested in the 105mm recoil mechanism of the M1 (M68 gun mount) at Aberdeen Proving Ground, MD,[25] Testing had to be suspended prematurely because of high recoil cylinder oil pressures. This confirmed the necessity of hardware modifications for the recoil mechanism.

In 1988, firing tests were conducted at Watervliet Arsenal with NFH in an M140A1 105E gun mount[26] (used in M60-series tanks) modified according to the findings of the previous testing at Aberdeen Proving Ground of the M68 gun mount. The piston grooves of the recoil mechanism were machined deeper radially, thus allowing less restricted flow around the recoil spring during firing. The tests were conducted at the temperature range of 0 to 75°F with regular M467 and upweighted M490 rounds. All recoil fluid pressures stayed within acceptable limits.

AIRCRAFT AND 8,000 PSI HYDRAULIC SYSTEM COMPONENTS

With the decision to develop a nonflammable hydraulic fluid for future aircraft came the requirement to develop the system components required for such a new fluid. The primary characteristics of CTFE hydraulic fluids to be considered in the design of the hydraulic system were studied and are discussed in a 1982 Boeing report, "Design Guide for Aircraft Hydraulic Systems and Components for Use with CTFE Nonflammable Hydraulic Fluids."[18]

Hydraulic system pressure ratings were raised from 3,000 to 8,000 psi because of the complementary requirements for a nonflammable hydraulic system, decreased hydraulic system weight, and increasing horsepower requirements of hydraulic systems.

Therefore, pumps operating at 8,000 psi, especially for aircraft applications, are being concurrently developed and characterized.[27] The Abex 8,000 psi pump has been tested with CTFE fluid and has demonstrated satisfactory performance.[28]

The 1984 McDonnell Douglas report[29] discusses the selection of a flight worthy hydraulic system which utilizes a CTFE base hydraulic fluid. Aircraft selection, hardware and concept definition, systems and weight analysis, reliability, and life cycle costs are reported. An extension of this research is presented in a 1985 report.[30] No insurmountable difficulties were encountered.

More recently, McDonnell Douglas, under contract to the Air Force, has designed and tested several low energy concepts and the various required components directed at 8,000 psi hydraulic system technology using CTFE: variable pressure pump, overlapped main control valves, flow augmentation and load recovery valves, and a full up variable pressure system.[31] These four concepts have been adapted for the Nonflammable Hydraulic Power Systems for Tactical Aircraft (NHPSTA) Program.

The objective of the NHPSTA Program was to develop and demonstrate an advanced hydraulic system designed to operate at a maximum pressure of 8,000 psi and to use CTFE hydraulic fluid. This Program, the culmination of the work of several programs, is nearing completion, with a 550-hour endurance test of the laboratory technology demonstrator scheduled for early 1990.[32]

SECTION V. HAZARD, ENVIRONMENTAL, AND DISPOSAL CONSIDERATIONS

Final results of WPAFB's toxicological studies on the CTFE base hydraulic fluid were not available at publication of this report. However, the initial results showed that at temperatures below 500°F (260°C), the fluid has low toxicity in acute studies by the oral, dermal, and inhalation routes and was negative in a delayed neurotoxicity study. The fluid also showed minimal eye irritation, negative skin irritation, and mild sensitization. Some effects from prolonged low level inhalation exposure may be experienced, but whether this is reversible or significant is not yet known. A Materiel Safety Data Sheet (MSDS) for the CTFE base stock from Halocarbon Products Corporation is in Appendix B.

At temperatures above 580°F (304°C), CTFE is subject to thermal cracking with rapid breakdown occurring above 620°F (327°). The breakdown products in air are toxic, acidic substances. This breakdown could occur when the hydraulic fluid comes in contact with an open flame or lighted cigarette.

Because of its high molecular weight, the CTFE oligimer should not cause ozone layer damage like other chloroflourocarbons.

Recycling is being considered to avoid hazardous waste disposal and to reduce overall costs.

SECTION VI. COST STUDIES

In 1986, a cost-benefit analysis comparing nonflammable hydraulic fluid and the Enhanced Automatic Fire Extinguisher System (EAFES) for use in the M60 and M1 was performed. The cost/benefit analysis was limited to those costs associated with the development and testing of each alternative. The study concluded that the EAFES should be pursued as the solution to hydraulic fluid vulnerability since nonflammable hydraulic fluid was more expensive for development and testing than EAFES. Unfortunately, the study did not address total life cycle costs and not all data was validated.[33]

A cost and benefit analysis base on advantages of an 8,000-psi system and the savings attributable to a reduction in fire losses in aircraft was made by an Air Force graduate student.[34] In comparing CTFE with MIL-H-83282, cost savings alone would justify the use of CTFE if only one aircraft with an 8,000-psi system or two aircraft with 3,000-psi systems were saved from destruction by fire. The real advantage of CTFE becomes more apparent in a combat situation because of the increase in survivability with CTFE.

An additional life cycle cost benefit study of the use of nonflammable hydraulic fluid in existing armored vehicles would be valuable to reconsider the life cycle costs for a nonflammable fluid retrofit.

SECTION VII. DRAFT SPECIFICATION DISCUSSION

The CTFE base stock was evaluated and characterized,[6] additives were found so that an NFH meeting the target requirements was formulated, elastomer materials have been developed which are reasonably satisfactory, and a specification was drafted by the Air Force (Appendix A). This draft specification describes a CTFE base hydraulic fluid for use in the temperature range –54 to 135°C. Since Army and Air Force NFH requirements are the same, this specification, describing a nonflammable hydraulic fluid for advanced aircraft and for armored combat vehicles, is being jointly developed by the Air Force and the Army.

SECTION VIII. DESIGN CONSIDERATIONS

From the studies conducted, it has been concluded that the CTFE base NFH is a truly nonflammable fluid, which should be considered in the design of future combat vehicles such as those planned within the Heavy Forces Modernization (HFM) Program. The technical implications of implementation in future design armored vehicles are manageable, as confirmed in the reports by Cadillac Gage[24] and Watervliet Arsenal.[26] However, the following considerations must be addressed:

- ❐ Replacement of seals and other elastomeric components with CTFE-compatible materials (e.g., Viton A-GLT, MIL-R-83485).
- ❐ Restriction on some metallurgical materials (e.g., brass and bronze).
- ❐ Modification of hydraulic system servo-mechanisms.
- ❐ Modification of gun recoil systems.
- ❐ Use of sealed fluid reservoir systems.
- ❐ Possible adoption of a higher pressure system.

The retrofit in existing hydraulic systems of fielded armored vehicles is technically feasible. Small hardware changes in the servo-mechanism and deeper piston grooves in the recoil mechanism mount are necessary and all elastomers would have to be replaced. In view of the investment that each individual vehicle represents, it appears that a full-fledged cost analysis for a retrofit of the M1 fleet is fully warranted.

SECTION IX. RECOMMENDATIONS FOR ADDITIONAL TESTING

If the NFH is considered for implementation, the following projects and studies which have not been done due to limited funding should now be initiated.

1 A field performance test of NFH in an M1A1 modified to accommodate this fluid (modified servo-mechanism and gun recoil system). This test would assure user acceptance of the NFH.

2 A study to develop reclamation procedures for used NFH. Reclamation of used fluid would tremendously impact the cost of this fluid and at the same time avoid environmental and waste disposal problems, which must be considered for all future fluids and weapon systems.

3 Continuation of research and development, which is currently underway under Air Force sponsorship, to develop non-proprietary additives, since the formulated NFH has one proprietary component.

4 A toxicity study of the decomposition products of the heated fluid. Although CTFE has been certified nontoxic by the Surgeon General, little is known about the nature of decomposition products and their toxicity.

REFERENCES

1 *Air Force Nonflammable Hydraulic System Materials Development*, SAE 851908, Snyder, Gschwender, Warner, and Fultz, Air Force Wright Aeronautical Laboratories and University of Dayton Research Institute, October 1985.

Abstract (abbreviated)

. . . This paper describes the materials research and development programs essential to the successful development of a totally nonflammable hydraulic system. Both hydraulic fluid and elastomeric seal development efforts are described. Research to date has successfully developed fluid and seal materials that have –54°C to 135°C temperature capability and proven operational pressure capability up to 27.6 MPa. Additional data are presented on materials development programs directed toward the more ambitious requirements of –54°C to 175°C temperature capability and operational pressure capability of 55.2 MPa . . .

. . . (proliferation of hydraulic systems, aircraft hydraulic fluid fires, flammability of MIL-H-5606 and MIL-H-83282) . . . A totally nonflammable hydraulic system has been an ultimate goal over the years. . . . The most desirable approach to a nonflammable hydraulic system would be to use a nonflammable hydraulic fluid in current hydrocarbon designed systems. This approach was abandoned after unsuccessful attempts by many different organizations, including our laboratory, the Navy, and industry, over the years.

Topics Covered in this Report

Fluid: flammability, target properties, lubricity, antirust, CREP test, thermal stability, –54°C to 175°C fluid, additives

Sealing materials and sealing systems: development of improved elastomers, dynamic elastomer testing, the chew tester and results, MTS tester, TRW tester, aircraft brake system seal testing

2 *Nonflammable Aircraft Hydraulic Systems Development*, SAE 821566, Snyder, Gandee, Gschwender, Graham, Berner, and Campbell, Air Force Wright Aeronautical Laboratories, October 1982.

Abstract

To eliminate the hazards associated with hydraulic fluid fires resulting from aircraft accidents and component failures, the Air Force established a program to develop a

nonflammable aircraft hydraulic system using a nonflammable fluid over the −54°C to 135°C temperature range. The Air Force is developing a chlorotrifluoroethylene oligimer base fluid, compatible elastomeric seals, and necessary hydraulic component/system redesign. The status of this program is discussed which includes a summary of the flammability tests, fluids and seal development, and performance testing of candidate materials in hydraulic components/systems.

Topics Covered in this Report

Flammability Assessment: heat of combustion, auto ignition temperature, hot manifold test, spray atomization

Fluid physical property requirements

Additive development: lubricity, metal passivators, rust inhibitors

Viscosity reduction

Screening of elastomer materials

Dynamic testing of candidate seal materials

Boeing component/system work: hydraulic pumps, flight control servo-actuators, transmission line tubing, reservoir, heat exchanger, valves, filters.

3 *Development of a Nonflammable Hydraulic Fluid for Armored Vehicles: Part I*, BRDEC Report No. 2401, AD B08790, Conley and Jamison, Belvoir Research, Development and Engineering Center, February 1984.

Abstract
The objective of this study is to develop a nonflammable hydraulic fluid that is compatible with the components of existing systems. To be a viable candidate, the fluid must be compatible with existing elastomeric seal materials. This report covers the efforts in formulating and testing Chlorotrifluoroethylene Oligimer (CTFE) base fluids with nitrile rubber seals that are commonly used in present armored equipment.

4 *Fluids, Lubricants and Elastomer Materials*, AFWAL-TR-86-4083, Davis, G. Chen, L., Chen, Eapen, Gultz, Hahn, Lawless, Mortimer, Sharma, Stropki, and Wical, University of Dayton Research Institute, November 1986.

Abstract (abbreviated)
. . . The synthesis and evaluation of various candidate nonflammable hydraulic fluids is also discussed. Synthesis and evaluation of various model compounds was conducted in an effort to establish the relationship between chemical structure and the physical properties of selected fluid classes. Commercially available fluids were also extensively

evaluated for their conformance to target specifications for new and improved hydraulic fluids. . . . Traction studies were performed on various lubricants to better define their lubricant behavior. Elastomers were compounded and mechanically evaluated for use in hydraulic systems for nonflammable fluids. Various high performance elastomeric materials were compounded and evaluated for advanced aerospace systems.

5 *Fluids, Lubricants, and Elastomer Materials*, AFWAL-TR-86-4130, Davis, G. Chen, L., Chen, Eapen, Fultz, Hahn, Lawless, Mortimer, Sharma, Stropki, and Wical, University of Dayton Research Institute, January 1987.

Abstract (abbreviated)

. . . The report covers the synthesis of nonflammable fluid candidates and silahydrocarbon based fluids. Several model compounds of these classes of fluids were also synthesized for further structure/property relationship studies. Various commercially available chlorotrifluoroethylene (CTFE) fluids were characterized and extensively evaluated as potential nonflammable fluids. . . . The traction behavior of several advanced fluids was determined on the MLBT traction rig. Elastomers were compounded and evaluated for use with the CTFE fluids. . . .

6 *Fluids, Lubricants and Elastomer Materials*, AFWAL-TR-88-4089, Davis, G. Chen, L., Chen, Eapen, Fultz, Hahn, Lawless, Miller, Mortimer, Schreiber, Sharma, and Wical, University of Dayton Research Institute, July 1988.

Abstract (abbreviated)

. . . This report covers the synthesis of various model compounds of chlorotrifluoroethylene (CTFE) fluids which were used for structure-property studies. . . . Nonflammable hydraulic fluids based on CTFE were extensively investigated, fully characterized and mechanically evaluated in hydraulic pump stands. . . . The traction properties of various fluids were determined and the data was used to develop a new traction model. Elastomeric materials were compounded and evaluated for various aerospace applications. Primary emphasis was on development of seals for CTFE nonflammable fluids. Dynamic tests were conducted on the most promising seal materials. . . .

7 *Discussion of Hydraulic Fluid Flammability Hazards*, AFLRL Report No. 95, AD A054560, Wright, US Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, December 1977.

Abstract

Hydraulic fluid flammability has been evaluated for fire-resistant fluid candidates and approved fluids. Hazards directly related to the M60A1 tank have been discussed. A

systematic assessment of flammability modes and ignition sources is presented. Experimental results indicate that mist flammability is more related to exposure conditions than to hydraulic fluid classes. Pool burning has been shown to be a major hazard, and the higher flash point fluids have been shown to provide a substantial margin of safety relative to conventional petroleum base fluids. Results of ballistic tests using 20mm HEIT projectiles demonstrated residual burning on the backstop (analogous to pool burning) only when conventional petroleum base fluids were evaluated, otherwise, only a transient mist fireball was observed.

8 *Hydraulic Fluid Development*, Letter Report, Wright, US Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, June 1979.

Abstract
This report discussed flammability characteristics of various hydraulic fluids based upon various flammability tests performed. A tentative vulnerability rating for each fluid was assigned, based upon the judgment of experienced flammability personnel. According to this merit rating scheme, the chlorofluorocarbon hydraulic fluid received a perfect score of 100, compared to MIL-H-6083 with a score of 32 and MIL-H-46170 with a score of 49.

9 *A Technique for Evaluating Fuel and Hydraulic Fluid Ballistic Vulnerability*, AFLRL Report No. 89, AD A055058, Wright and Weatherford, US Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, December 1977.

Abstract
A relatively inexpensive ballistic test procedure has been developed for evaluating the relative fire vulnerability of various fluids of interest for Army applications. The technique employs 20mm HEIT projectiles fired into partly-filled fluid containers. It yields repeatable results which establish both transient fireball effects and residual burning tendencies. Appropriate experimental procedures and conditions, such as target fluid temperature, were established, and the efficiency and repeatability were evaluated by conducting a total of 184 experiments, 81 of which are tabulated herein. These latter experiments were conducted with fire-safe fuel (FSF) and fire-resistant hydraulic (FRH) fluid candidates. The resulting experimental data agree with flammability measurements made with laboratory and bench-scale techniques and provide an apparently realistic assessment of ballistic vulnerability. It is planned to evaluate the realism of the ballistic exposure by arranging for a series of Army-conducted full-scale ballistic tests.

10 *Standardization of Flammability Tests for Hydraulic Fluids*, AFLRL Report No. 181, AD A146468, Kanakia, Dodge, Callahan, and Wright, US Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, September 1983.

Abstract
The modification of the physical and chemical properties of various fluids developed for use as hydraulic fluid has necessitated the development or modification of tests required to evaluate the performance criteria of these fluids. The Federal Government utilized certain Federal Test Methods and ASTM flammability test procedures in fluid specification requirements to determine the relative flammability of fluids currently being developed for use as hydraulic fluids. These tests include the flash and fire points, autoignition temperatures, flame propagation, high-pressure spray, and hot manifold ignition test procedures. Unfortunately, as fluid composition and applications change, new or modified tests must be developed to provide accurate assessments of the fluids' performance. This report presents the results produced by a systematic study of mist-flammability parameters that will lead to development of a standard mist-flammability test for hydraulic fluid specification purposes.

11 *Monthly Progress Report for the period 1 August - 31 August 1981 on Basic and Applied Fuels and Lubricants Research*, US Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, August 1981.

Abstract
The objective of this program was to perform flammability testing of various hydraulic fluids, including Halocarbon AO-8 Base Fluid (CTFE). The Halocarbon AO-8 fluid would not ignite in the wick flame propagation test and in testing of the ignition of fluid streams/mists by heated surfaces.

12 *Determination of the Flammability Characteristics of Aerospace Hydraulic Fluids*, Lubrication Engineering, Volume 37, 12, 705-714, Snyder, Wright-Patterson Air Force Base, Krawetz and Tovrog, Phoenix Chemical Laboratory, December 1981.

Abstract
The hazards associated with the flammability characteristics of aerospace hydraulic fluids are well known. In an effort to reduce these hazards, commercial airlines converted to the use of a phosphate-ester-based, fire-resistant hydraulic fluid with the advent of jet aircraft in the early 1950s. More recently, some of the military aircraft were converted to a compatible, synthetic-hydrocarbon-based hydraulic fluid for the same reason. The flammability characteristics of these and other aerospace hydraulic fluids and test methods used to determine them are discussed. Since a deficiency exists

in the area of determination of the flame and/or fire-propagation characteristics of fluids and lubricants, a new test method was developed and is described. The degree of correlation of the data from this test method with other flammability tests is discussed.

Conclusions

A number of flammability tests (flash point, fire point, autogenous ignition temperature, stream hot-manifold ignition temperature, heat of combustion, gunfire resistance, and horizontal flame propagation) were performed on current and developmental hydraulic fluids and the results are summarized. The chlorofluorocarbon base and fluoroalkylether base fluids demonstrated such tremendously improved fire resistance over the hydraulic fluids currently called "fire-resistant" that these fluids are being considered nonflammable hydraulic fluids.

13 *Development and Mechanical Evaluation of Nonflammable Aerospace (–54°C to 135°C) Hydraulic Fluids*, Lubrication Engineering, Volume 38, 1, 41-51, Snyder, Gschwender, and Campbell, Wright Patterson Air Force Base and University of Dayton Research Institute, January 1982.

Abstract

The development and mechanical characterization of candidate nonflammable aerospace hydraulic fluids for use over the temperature range of –54°C to 135°C is described. The criteria of selection of the base fluids are presented and discussed. Formulation of the base fluids to enhance their viscosity-temperature and antiwear characteristics is discussed. Bulk modulus data are presented for the candidate fluids. Results from the mechanical characterization of candidate fluids in typical aerospace hydraulic pumps are presented.

Conclusions

Two excellent candidate fluids have undergone exploratory development and demonstrated the potential of meeting the Air Force requirements for a nonflammable hydraulic fluid suitable for use over the temperature range of –54°C to 135°C in aerospace applications. Formulation of both candidate fluids with property enhancing additives has shown promise of overcoming fluid deficiencies. Bulk moduli data have been reported and compared to data of the currently used Air Force hydraulic fluid. Elastomer and hardware material compatibility have been extensively investigated and pump test evaluation has demonstrated the suitability of these fluids for use in current design aerospace hydraulic system components.

14 *Fireproof Hydraulic Brake System*, AFWAL-TR-2072, Huling and Hillman, Boeing Military Airplane Company, October 1985.

Abstract

The principal specific objective of the Fireproof Hydraulic Brake System (FHBS) program was to develop a two-fluid (MIL-H-5606 and CTFE) fireproof brake system that has equivalent or better stopping performance and safety when compared to the existing C/KC-135 Mark II antiskid, five rotor brake system. The program's generalized objective was to show the feasibility of developing hardware for a two-fluid, nonflammable braking system for any aircraft.

Since the majority of hydraulic fluid fires are initiated by hot brakes in the landing gear/wheel well areas, a system design that restricts the use of the CTFE to the brake system minimizes the weight increase while significantly reducing the aircraft fire hazard.

15 *Fireproof Hydraulic Brake System*, Report No. 4950-FTR-86-1, AD A167774, Dillard, Wright Patterson Air Force Base, April 1986.

Abstract

The Fireproof Hydraulic Brake System (FHBS) flight test program verified that the FHBS is a feasible method of eliminating aircraft hydraulic fluid fires ignited by hot brakes. The FHBS uses a new nonflammable hydraulic fluid, chlorotrifluoroethylene (CTFE), in the wheel well and landing gear area while retaining standard hydraulic fluid (MIL-H-5606) in the rest of the aircraft hydraulic system. The two fluids were separated downstream of the antiskid valve by a reservoir/separator unit. A C-135E was used as the test aircraft. The modification consisted of instrumentation to monitor brake system parameters and the FHBS installation for the left outboard wheel pair. The testing consisted of maximum effort braking runs at light aircraft gross weights to induce antiskid cycling. The FHBS was evaluated subjectively by the test pilot and objectively by comparing its performance with that of the standard C-135 brake system established by baseline testing.

Conclusions

The FHBS is a feasible concept. No significant difference in performance could be detected. The FHBS was recommended for other aircraft models.

16 *Fragment Attack on Ground Vehicle Hydraulic Lines,* Technical Report BRL-TR-2661, AD-B095255, Finnerty, Meissner, and Copland, US Army Ballistic Research Laboratory, July 1985.

Abstract

The vulnerability of generic hydraulic tubing to fragment attack was experimentally determined for both empty and pressurized lines. Representative sizes and velocities of fragments were chosen to simulate behind armor debris (BAD). The effectiveness of thin steel overlays to protect hydraulic lines from perforation by BAD was quantified. It was found that overlays should be quite effective in protecting lines. The ability of fire suppression materials to prevent ignition of fire resistant hydraulic (FRH) fluid was investigated. Some protection was found against ignition of fluid escaping from a perforated line. No attempt was made to optimize either the type or amount of suppression agent. However, hot pressurized FRH fluid escaping from perforated lines was readily ignited given an adequate ignition source.

17 *Evaluation of Evaporation Loss of Chlorotrifluoroethylene Fluid in an M60 Hydraulic Fluid Reservoir*, BRDEC Report No. 2417, AD A154985, Rhee, Belvoir Research, Development and Engineering Center, December 1984.

Abstract

The objective of this study was to evaluate the potential volatility problem of Chlorotrifluoroethylene (CTFE) fluids if used in the existing hydraulic systems of armored vehicles. Laboratory simulated service evaporation tests were conducted using the actual M60 hydraulic fluid reservoir at 160°F for three weeks and an additional three weeks at 200°F. The fluids used in these tests were the petroleum-based MIL-H-6083 (OHT) which was selected as the reference fluid and the experimental CTFE fluid which has been chosen as the candidate base material for the nonflammable hydraulic fluid currently under development. The test results showed negligible evaporation loss in both fluids under the conditions of the test performed. Therefore, it is concluded that volatility should not present any problem in the future use of CTFE-base fluids in the existing hydraulic systems.

18 *Design Guide for Aircraft Hydraulic Systems and Components for Use with Chlorotrifluoroethylene Nonflammable Hydraulic Fluids*, AFWAL-TR-80-2111, Raymond, Boeing Military Airplane Company, March 1982.

Abstract

The purpose of this design guide is to document the major physical properties of chlorotrifluoroethylene (CTFE) polymer-based nonflammable hydraulic fluids and special considerations which must be observed in the design of hydraulic systems and

components intended for use with these fluids. Properties of the standard petroleum-based hydraulic fluid per specification MIL-H-5606 are also included for comparison; and, the special design considerations used for designing systems and components for use with MIL-H-5606 hydraulic fluid.

19 *Corrosion and Lubricity Testing of Nonflammable USAF Formulated CTFE Base Hydraulic Fluid*, BRDEC Report No. 2473, Smith, Belvoir Research, Development and Engineering Center, August 1988.

Abstract

The objective of this study was to evaluate the antiwear and anticorrosion properties of the US Air Force's latest nonflammable hydraulic fluid formulation, a chlorotrifluoroethylene oligimer containing an antiwear additive and an anticorrosion additive. This formulation, referred to as NFH, is stable to 135°C. The NFH was tested according to ASTM D1472 and D1748, the Federal Test Standard 791C Methods 5322.1 and 5308.6, and the corrosion rate evaluation procedure (CREP). The data contained in this report is compared with the chlorotrifluoroethylene with no additives and the present fire resistant hydraulic fluid, Military Specification MIL-H-46170. The antiwear and anticorrosion properties of the formulated NFH improved over the base fluid with no additives.

20 *Nonflammable Hydraulic System Seal Materials*, AFWAL-TR-84-4097, AD B104099, Martin, TRW, Inc., September 1984.

Abstract

An R&D program was conducted to develop elastomeric seals and anti-extrusion devices compatible with chlorotrifluoroethylene (CTFE) nonflammable hydraulic fluid over the temperature range of –54°C (–65°F) to 135°C (275°F) at system pressures up to 55.2 MPa (8,000 psi). The program consisted of two phases. Phase I was development of a primary elastomeric seal and anti-extrusion device, referred to as a sealing system, for a 20.7 MPa (3,000 psi) aircraft brake system. Phase II was development of a sealing system for aircraft with operating pressures up to 55.2 MPa (8,000 psi).

Compounding of elastomers, development of resins, and design and fabrication of seals were performed under the program. Dynamic sealing tests were conducted using equipment designed and built specifically for this purpose.

For Task I brake piston seals at 20.7 MPa (3,000 psi), a sealing system of an EPDM O-ring and two each two-turn spiral anti-extrusion rings made from lightly-loaded Teflon performed the best.

For Task II actuator rod and piston seals at 55.2 MPa (8,000 psi), a sealing system from Greene, Tweed & Co. identified as a GT Cap Seal performed the best.

Recommendations are made regarding hardware design parameters, anti-extrusion rings and elastomer compounds intended for O-rings and alternative (e.g., energizer) approaches to sealing high pressure CTFE hydraulic systems.

21 *High-Temperature / Pressure Sealing Systems for Advanced Aircraft and Missile Hydraulic Systems*, AFWAL-TR-87-4050, Martin, TRW Electronics & Defense Sector, January 1987.

Abstract
An R&D program was conducted to develop sealing systems for two different applications. The first was for cruise missile applications with MIL-H-27601 hydrocarbon fluid over a temperature range of -54°C (-65°F) up to +316°C (600°F) where long term static storage before use was a major factor. The second was for advanced aircraft applications with nonflammable CTFE fluid over a temperature range of -54°C (-65°F) up to +177°C (350°F) where a very large number of actuations was a major factor. Hydraulic system pressure ranges up to 55.2 MPa (8,000 psi).

For the aircraft application, two capped elastomer seal designs using PEEK back-up rings successfully sealed 55.2 MPa (8,000 psi) CTFE fluid for 10 million cycles at 177°C (350°F).

22 *Compatibility of Experimental Nonflammable Hydraulic Fluids with Elastomeric Seals*, BRDEC Report No. 87/172/UVFY, Touchet, Belvoir Research, Development and Engineering Center, 2 April 1987.

Abstract
This work was performed to determine the compatibility of elastomeric seals with candidate nonflammable hydraulic fluids being developed for the Army family of tracked vehicles.

It was concluded that nitrile seals currently being used in hydraulic systems on Army tracked vehicles are not compatible with CTFE based fluids. When CTFE base fluids are contaminated with hydrocarbon fluids, metal corrosion and, in some cases, the deterioration of the seals themselves is accelerated when copper ions are available.

GT-818 (an EPDM seal supplied by Greene Tweed) was recommended as the first choice seal material for consideration for Army use with the Air Force formulated CTFE fluid. The E/S-3 formulation (an in-house formulation utilizing Royaltherm 1711 silicone modified EPDM polymer and Ricon 154 resin) should be optimized further since it showed great promise. Both seals should be evaluated at –60°F and should be

submitted to the Air Force dynamic seal tests. If contamination cannot be avoided, the candidate seals would have to be compatible with contaminated CTFE fluid.

23 *Investigation / Test of High Density Semi-Formulated Nonflammable Hydraulic Fluid, Chlorotrifluoroethylene*, Cadillac Gage Report No. 85-128, Alfoldy and O'Rourke, Cadillac Gage Company, 15 December 1985.

Abstract
This investigation was conducted to determine the effect of the high density of the semi-formulated, nonflammable hydraulic fluid in the M1 Weapon and Turret Control System. The candidate, high density, semi-formulated, nonflammable hydraulic fluid is sufficiently different from MIL-H-46170 that substitution in the M1 Weapon and Turret Control system would require modification to the hardware.

The new oil will cause reduced gains from the pilot and third stage valves which will result in noticeable performance degradation. To regain the lost performance, it would be necessary to make small modifications to the electronics to reoptimize loop gains and to resize the metering orifices in the third stage valve to regain peak velocities. The pilot valves have sufficient reserve flow capacity that they would not have to be changed.

The low temperature performance will improve significantly due to lower viscosity. It may be possible that with the new oil the electronic modification made to compensate for the reduced low temperature performance with the present oil can be removed. This, together with the gain optimizations and increased slot width in the third stage, may improve performance over the entire operating temperature range.

24 *Hydraulic System Performance Tests Using CTFE Hydraulic Fluid, Chlorotrifluoroethylene*, Cadillac Gage Report No. 88-101, Willard P. Alfoldy and Gary M. Bonnell, Cadillac Gage Textron, 22 February 1988.

Abstract
Tests results indicate that lost performance in the M1 Weapons and Turret Control System as defined by reduction in bandwidth associated with direct substitution of CTFE hydraulic fluid can be restored through modification of the hardware.

A 30 percent increase in the servo amplifier electrical gain is required to compensate for the reduction in the M1 pilot EHV flow gain.

The M1 Elevation Servo-mechanism third stage spool bandwidth at room and high temperatures remains 13 percent less as a result of the higher density of CTFE and its effects on the pilot EHV internal loop gain and natural frequency. However, the third

stage spool bandwidth remains significantly higher than other natural frequencies within the system and, therefore, should cause no noticeable performance degradation.

Low temperature performance was significantly improved while operating on CTFE due to the lower viscosity of the fluid. At –25°F, and using the modified electrical gains, the bandwidth of the M1 Elevation Mechanism third stage spool was seven times higher while operating on CTFE as opposed to operating on MIL-H-46170. This substantial increase in bandwidth allows the elevation at cold temperatures. As a result, it is likely that the system problems associated with cold temperature start-up will be reduced or eliminated.

Conclusions and Recommendations

The electronics and slot gain modifications can be made to accommodate the use of CTFE. Cadillac Gage recommends and would strongly support a vehicle test program.

25 *Special Study of Gun Mount, 105-MM, M68 for M1 Tanks, with Nonflammable Hydraulic Fluid*, TECOM Project No. 1-WE-105-068-115, Aberdeen Proving Ground, 18 June 1984.

Abstract

The test objective was to obtain data from instrumented firing tests under environmental conditions using CTFE, which was being proposed for use in the 105-mm recoil mechanism of the M1 Abrams Tank. The testing was suspended after the first five rounds because the recoil oil pressure exceeded the recommended maximum design pressure of 2,500 psi. It was concluded that the CTFE density has a considerable effect on the recoil system pressure and modifications to recoil systems must be made.

26 *Results of CTFE Fluid Test at Wright-Malta Corporation, Malta, New York*, Benet Laboratories, Task No. 1, John S. DiFucci, Wright-Malta Corporation, March 2, 1988.

Abstract

The test objective was to perform firing tests, using CTFE, of a modified version of the M140A1 gun mount at 0°, 70°, and 120°F. The M140A1 105E program modified gun mount, which has deeper grooves in the recoil piston, was used for this test, since this modification was expected to lower the maximum recoil oil pressures. The recoil stroke, recoil, and counter recoil times, the oil pressure vs. time curve, and the maximum oil pressures were slightly different from those typical of operation with MIL-H-46170, but were within acceptable limits. The mount leakage was not unusual. It was concluded that the possibility of integrating CTFE into the M140A1 was promising. Minimal modification of the mount hardware would be necessary (.125 inch deeper radially machining of piston grooves) and a compatible seai would be required.

27 *Hydraulic Pumps for High Pressure Nonflammable Fluids*, SAE 851911, Halat, Vickers, Inc., October 1985.

Abstract

Design considerations that 8,000 psi and nonflammable fluids have upon an aircraft inline piston hydraulic pump are presented. The influence of the major physical properties on one nonflammable fluid, chlorotrifluoroethylene (CTFE), are discussed as well as the influence of the hydraulic system.

Hydraulic pump pressure, based on experience with the US Navy Lightweight Hydraulic System (LHS), can be increased to 8,000 psi without encountering major problems. Utilization of CTFE as a hydraulic fluid shows considerable promise.

The performance characteristics of an 8,000 psi pump are presented. The paper includes a summary of the high pressure operating experience.

The paper concludes with a summary of the Wright Patterson Air Force Based contract for three 400-gpm, 8,000-psi CTFE pumps.

28 *Compatibility Test Report on 8,000 psi Hydraulic Pump with AO2 (CTFE) Fluid*, Abex Report No. AER-883, Kouns, Abex Corporation, Aerospace Division, December 1983.

Abstract

The objective of the testing was to determine the compatibility of the Halocarbon Corporation CTFE formulation AO-2 with the Abex 8,000 psi pump. The pump performed satisfactorily for the 500-hour endurance test.

29 *Flight Worthiness of Fire Resistant Hydraulic Systems*, AFWAL-TR-84-2085, Jeffery, Merrell, Pierce, Stevens, and Young, McDonnell Douglas Corporation, December 1984.

Abstract

This program established the design technology required to utilize CTFE base fluid in modern high performance fighter and cargo/bomber aircraft hydraulic systems with minimum weight penalty and assurance of acceptable performance.

It was concluded that the CTFE weight penalty could be controlled by using 8,000 psi operating pressures and other concepts. The reduced kinematic viscosity of CTFE at low temperatures is desirable for better low temperature performance. It was recommended that the program continue to verify system performance.

30 *Nonflammable Fluid and 8,000 psi Technology for Future Aircraft Hydraulic Systems*, SAE 851909, Binns, Campbell, Pierce, and Young, Wright Patterson Air Force Base and McDonnell Aircraft Co., October 1985.

Abstract (abbreviated)
. . . A nonflammable fluid, Chlorotrifluoroethylene (CTFE), was identified, however, its weight was over 2.2 times heavier than conventional fluid. This paper discusses the system design approaches, component design, and test results of an overall program to establish technology for use of the nonflammable fluid in new aircraft. This will include the tradeoff study results for selection of 8,000 psi as the pressure level, design approaches to control water hammer pressures, component and system design and evaluation. The status of the ongoing programs for investigating dynamic seals, pumps, and low energy consumption hydraulic concepts will also be presented.

Summary
To date, the overall program to provide technology for use of the CTFE nonflammable fluid in future aircraft hydraulic systems has not uncovered any insurmountable problem areas. To counteract weight penalties associated with CTFE fluid, the program has been directed toward 8,000 psi. Techniques have demonstrated that water hammer pressure transients can be controlled to not exceed system based pressure levels. A prototype pump and actuators have been successfully demonstrated for over 750 hours at 8,000 psi with CTFE fluid. The critical components and system aspects are being investigated in ongoing programs on high pressure pump and seal technology, low heat rejection, actuator stiffness, and improved fluid properties.

However, challenges being imposed by new aircraft requirements make it necessary that the 8,000 psi technology exceed the present 3,000 psi state-of-the-art. Future effort is required to reduce horsepower/heat rejection, develop components, materials and seals for higher temperatures, and improve system reliability and maintainability. Promising approaches have been identified for fulfilling these requirements and are being addressed by ongoing or planned programs. Overall, the technology advancements now being investigated in this program have so much potential that they are being seriously considered for the next production aircraft.

31 *Low Energy Consumption Hydraulic Techniques*, AFWAL-TR-88-2062, Greene, Jeffery, Lohe, Pehowski, Pierce, Wieldt, and Young, McDonnell Douglas Corporation, August 1988.

Abstract
This report documents the efforts to develop and test low energy consumption hydraulic techniques. Included is a discussion of the efforts to select and analyze a baseline hydraulic system (Phase I) and conduct trade studies on various candidate design approaches which could reduce weight and power consumption (Phase II). In addition, the report discusses the development of a test plan (Phase III) and the results of an endurance test (Phase IV).

This program was directed at 8,000 psi hydraulic system technology using a nonflammable hydraulic fluid chlorotrifluoroethylene (CTFE) although the concepts developed could be applied to any fluid at any system pressure.

The concepts selected for test were variable system pressure, flow augmentation with load recovery valves and overlapped main valves. These concepts were embodied and tested with a servo-controlled hydraulic pump and a dual tandem flight control servo-cylinder. The concepts were successfully tested and showed that significant weight and energy savings could be achieved on advanced aircraft.

32 *Nonflammable Hydraulic Power System for Tactical Aircraft*, WRDC-TR-89-2026, Greene, Harmon, Jeffery, Lohe, Pierce, Roach, Shehan, Wieldt, McDonnell Aircraft Company, May 1989.

Abstract
The Nonflammable Hydraulic Power Systems for Tactical Aircraft Program objective was to develop and demonstrate an advanced hydraulic system designed to operate at a maximum pressure of 8,000 psi and use an Air Force-developed, nonflammable fluid, chlorotrifluoroethylene (CTFE). It followed four previous programs directed at this technology at Boeing and MCAIR. It was further complemented by three other Air Force-sponsored programs which embrace either 8,000 psi, CTFE or both. These programs are being conducted at: Parker Controls Systems Division of Parker Hannifin Corporation (Seal Evaluation); Vickers Incorporated (High Pressure Pump Development); and Rockwell International (High Pressure Distribution System Evaluation).

In order to place the technology in a low risk category which can be embraced for future programs, many complementary technologies are being addressed which greatly enhance the use of the nonflammable fluid at high operating pressures. Power efficient technologies, which have resulted from previous programs such as Low Energy Consumption Hydraulic Techniques (LECHT), were used to improve the efficiency of the system and reduce heat exchanger requirements to a minimum. Advanced construction materials were exploited to provide minimum weight and long fatigue life. Redundancy management has been addressed with proven techniques such as multiple systems, reservoir level sensing shutoff valves, pressure operated shuttle valves, as well as introduction of a new device, the hydraulic integrity monitor (HIM). With expanded interest in airframe central powered engine nozzle actuators, the Program included several actuators designed for high temperature operation and included several advanced fluid cooling techniques.

In Phase V of the program, a 550-hour endurance test of the Laboratory Technology Demonstrator will be performed to exercise a complete aircraft shipset of hydraulic

central power equipment, about half of a complete fly-by-wire flight control set, a complement of engine nozzle actuators, and several other advanced actuation devices.

33 *Cost Benefit Analysis (CTFE vs AFES)*, Program Manager, Tank Systems, ATTN: AMCPM-GCM-SW, August 1986.

Abstract

Flammable hydraulic fluid is involved in about 20% of peacetime tank fires which costs about $1.6M per year for the Army's two main battle tanks. In combat, at least 10% of tank losses could be prevented if fire can be prevented. Tank fires can be avoided by prevention (nonflammable materials) and extinction (instantaneous fire suppression). The cost of CTFE development, including prototypes, comes to over $15M. The cost of developing EAFES is about $2.4M. It is recommended that EAFES be pursued to solve the problem of tank damage due to fire.

34 *A Cost and Benefit Analysis of Hydraulic Fluid Systems for the Next Generation of Tactical Aircraft*, AD A186 911, Mahony, Air Force Institute of Technology, September 1987.

Abstract

This study analyzed the life cycle costs, cost of fires, and benefits of using a new nonflammable hydraulic fluid (CTFE) in future tactical aircraft versus a fire retardant fluid (MIL-H-83282) currently used in tactical aircraft. The study assumed that future hydraulic systems will use 8,000 psi pressure. An analogy was made using a McDonnell Douglas Corporation study as the basis. This study compared MIL-H-83282 and CTFE at 8,000 psi showing weight as the primary difference. Therefore, this weight difference, the fluid price difference, and the fuel consumption of an F-15 were used to determined the life cycle cost difference between the two systems. Since the added weight was slight, only the additional fuel consumption to fly the extra weight was significant. The added life cycle costs for using CTFE was estimated at $11.4M in FY87 dollars.

However, CTFE will prevent hydraulic fires so an estimate of MIL-H-83282 fire costs was attempted. . . .

The differences in the benefits were primarily in the survivability and capability of the aircraft. Taking these differences together, CTFE is slightly better than MIL-H-83282 in peacetime. This difference becomes more pronounced in wartime.

Finally, a sensitivity analysis was conducted on the assumptions. Based on these analyses, a conclusion was made that CTFE was a viable alternative at 8,000 psi. However, further research is needed on the logistical problems related to the new pressure and fluid. Also, further study is needed on the effectiveness of MIL-H-83282 against the causes of hydraulic fires.

APPENDIX A
AIR FORCE DRAFT SPECIFICATION

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DRAFT

MIL-H-XXXXX
2 December 1989
PROPOSED DRAFT

MILITARY SPECIFICATION

HYDRAULIC FLUID, NONFLAMMABLE,
CHLOROTRIFLUOROETHYLENE BASE

This military specification is approved for use by all Departments and Agencies of the Department of Defense.

1. SCOPE

1.1 Scope. This military specification describes the characteristics of and provides the requirements for a chlorotrifluoroethylene base hydraulic fluid for use in hydraulic systems of aircraft and selected armored vehicles through the temperature range -54°C to +135°C (see 6.1). This fluid is identified by the military symbol NFH.

2. APPLICABLE DOCUMENTS

2.1 Government documents.

2.1.1 Specifications and standards. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS) and supplement thereto, cited in the solicitation (see 6.2).

SPECIFICATIONS

FEDERAL

PPP-C-96 - Can, Metal, 28 Gage & Lighter
PPP-D-729 - Drums, Shipping and Storage, Steel, 55 Gallon
PPP-P-420 - Plug and Flange, (for Drum Closure)
PPP-P-704 - Pail, Metal (Shipping, Steel, 1 through 12 Gallon)

MILITARY

MIL-R-83485 - Rubber, Fluorocarbon Elastomer, Improved Performance at Low Temperature, Type II

STANDARDS

FEDERAL

FED-STD-313 - Material Safety Data Sheets, Preparation and Submission of.

FED-STD-791 - Lubricants, Liquid Fuels and Related Products; Method of Testing.

MILITARY

MIL-STD-105 - Sampling Procedures and Tables for Inspection by Attributes

MIL-STD-290 - Packaging, Packing and Marking of Petroleum and Related Products

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Naval Publications and Forms Center, (ATTN: NPODS), 5801 Tabor Avenue, Philadelphia, PA 19120-5099.)

2.1.2 Other Government documents, drawings and publications. The following other Government documents and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues are those in effect on the date of the solicitation.

DEPARTMENT OF LABOR (DOL)

OSHA 29 CFR 1920.1200 Hazard Communication Interpretation Regarding Lubricating Oils.

(Application for copies should be addressed to the Superintendent of Documents, Government Printing Office, Washington, DC 20402).

2.2 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the documents cited in the solicitation (see 6.2).

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARD TEST METHODS

D 97 - Pour Point of Petroleum Oils.
D 130 - Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test.
D 445 - Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity).
D 664 - Neutralization Number by Potentiometric Titration.
D 892 - Foaming Characteristics of Lubricating Oils.
D 1744 - Water in Liquid Petroleum Products by Karl Fischer Reagent.

D 2879 - Vapor Pressure-Temperature Relationship and Initial Decomposition Temperature of Liquids by Isoteniscope.
D 4057 - Manual Sampling of Petroleum and Petroleum Products.
D 4172 - Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method).

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.)

NATIONAL MOTOR FREIGHT TRAFFIC ASSOCIATIONS, INC.

National Motor Freight Classification

(Application for copies should be addressed to the American Trucking Association, Inc., 1616 P Street, N.W., Washington, DC 20036.)

UNIFORM CLASSIFICATION COMMITTEE, AGENT

Uniform Freight Classification Rules

(Application for copies should be addressed to the Uniform Classification Committee, Room 1106, 222 South Riverside Plaza, Chicago, IL 60606.)

(Non-Government standards and other publications are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.)

2.3 Order of precedence. In the event of a conflict between the text of this document and the references cited herein, (except for related associated detail specifications, specification sheets or MS standards), the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. REQUIREMENTS

3.1 Preproduction sample. Unless otherwise specified (see 6.2), the preproduction sample shall be considered as first article sample and shall be subjected to first article inspection (see 6.3) in accordance with 4.2.

3.2 Material. The hydraulic fluids shall consist of chlorotrifluoroethylene (CTFE) base fluid formulated with additive materials to improve the lubricity and antirust characteristics. Recycled CTFE shall not be excluded from use. Additive materials that improve the low temperature flow and viscosity-temperature characteristics (pour point depressants and Viscosity Index improvers) shall not be permitted.

3.2.1 Base stock requirement. The properties of the base stock used in formulating the finished hydraulic fluid, before the addition of any additive materials, shall be in accordance with Table I when tested as specified in Appendix 30.1 and 30.2.

Table I

Properties of Chlorotrifluoroethylene Base Stock

Characteristic	Requirement
Unsaturation, minutes, minimum	60
Capillary gas chromatography, percent elution before trimer, maximum	11

3.3. Toxicity. The materials shall have no adverse effect on the health of personnel when used for its intended purpose. The fluid shall contain no components which produce noxious vapors in such concentrations as to be an annoyance to personnel during formulation or use under conditions of adequate ventilation when exercising caution to avoid prolonged contact with skin and while observing Occupational Safety and Health Administration (OSHA) guidelines. Questions pertaining to the toxic effects shall be referred by the procuring activity to the appropriate departmental medical service who will act as an advisor to the procuring activity.

3.3.1 Material Safety Data Sheets. Material Safety Data Sheets (MSDS) for each component ingredient of the finished product along with the finished product shall be prepared in accordance with FED-STD-313 (see 6.7). Questions pertinent to the effect of MIL-H-XXXXXX hydraulic fluid on the health of personnel, when used for its intended purpose, shall be referred by the acquiring activity to the appropriate medical service who will act as adviser to the acquiring activity.

3.4 Properties. The properties of the finished hydraulic fluid described herein shall be as specified in Tables II and III and in 3.4.1 through 3.4.9 when tested as specified in Table IV and the attached Appendix.

Table II
Properties of the Finished Fluid

Characteristic	Requirement
Viscosity in centistokes	
at -54°C, maximum	1200
at 38°C, minimum	2.9
at 135°C, minimum	0.60
Total acid number, maximum	0.6
Lubricity, four ball wear scar, millimeters, maximum	0.8
Vapor pressure at 121°C, kPa, maximum	13.3
Pour point, °C, maximum	-60
Corrosion of copper, maximum	3a
Heat of combustion, Kcal/kg, maximum	2750
Hot manifold ignition, °C, minimum	925
Low temperature stability	pass
Water, ppm, minimum	200
Storage stability	pass

3.4.1 Corrosiveness and oxidation stability.

3.4.1.1 Corrosiveness. When tested as specified in Federal Test Method Standard 5308, the change in weight of steel, aluminum alloy, magnesium alloy and cadmium subjected to the action of the hydraulic fluid shall be not greater than ± 0.2 milligrams per square centimeter of surface. The change in weight of copper under the same conditions shall be not greater than ± 0.6 milligrams per square centimeter of surface. There shall be no pitting, etching, nor visible corrosion on the surface of the metals when viewed under magnification of 20 diameters. Any corrosion produced on one surface of the copper shall be not greater than No. 3a of the ASTM copper corrosion standards. A slight discoloration of the cadmium shall be permitted.

3.4.1.2 Resistance to oxidation. When tested as specified in Federal Test Method Standard 5308, the fluid shall not have changed more than 5 percent from the original viscosity in centistokes at 40°C after the oxidation corrosion test. The total acid number shall not have increased by more than 0.20 from the acid number of the original sample. There shall be no evidence of separation of insoluble materials nor gumming of the fluid.

3.4.2 Swelling of synthetic rubber. When tested as specified in Federal Test Method Standard 3603, the volume increase of the fluorocarbon elastomer, Viton A-GLT (as referenced in MIL-R-83485, Am.1, type II) by the fluid shall be within the range 25 to 40 percent.

3.4.3 Solid particle contamination. When samples taken for particle count are tested in accordance with 4.6.3, in a clean, dust free atmosphere, the number of solid contaminant particles per 100 mL of the fluid shall not exceed the number specifed in Table III.

Table III
Solid Contaminant Particles

Particle Size Range (Largest) Dimension, Micrometers	Allowable Number (maximum) Each Determination Automatic Count
5-15	10,000
16-25	1,000
26-50	150
51-100	20
Over 100	5

3.4.4 Foaming characteristics. When tested at 25°C, as specified in ASTM D892, the foaming tendency and foam stability shall be determined. The foam volume at the end of a 5 minute blowing period shall not exceed 65 mL. The foam shall have completely collapsed at the end of a 10 minute settling period. (A ring of small bubbles around the edge of the graduate shall be considered complete collapse.)

3.4.5 Compatibility. The hydraulic fluid shall be compatible in all concentrations with each of the fluids approved under this specification when tested as specified

in 4.6.4. The hydraulic fluid shall be miscible with other approved fluids in all proportions from -54 to 135° C, in that no formation of resinous gums, sludges or insoluble materials shall occur.

3.4.6 Thermal stability. When tested as specified in Appendix 30.3, the hydraulic fluid shall not have changed more than 5.0 percent from the original viscosity in centistokes at 40°C and the total acid number shall not have increased by more than 0.20 over the original value of the fresh fluid. The change in weight of the steel balls shall be not greater than ± 0.2 milligrams per square centimeter of surface. The change in weight of the naval bronze under the same conditions shall be not greater than ± 0.5 milligrams per square centimeter of surface. There shall be no pitting, etching nor visible corrosion on the surface of the balls. The presence of black particles in the post test fluid shall also be considered a cause for failure. The test shall be invalid if the bomb weight loss exceeds 0.500 grams.

3.4.7 Corrosion protection. When tested as specified in Appendix 30.4, the hydraulic fluid shall afford protection against corrosion of polished steel panels by showing no more visible corrosion and no greater weight change than the reference panels that were immersed in Standard Reference Fluid A.

3.4.8 Bulk modulus. When tested as specified in Appendix 30.5, the isothermal secant bulk modulus of the finished fluid at 27.6 MPa and 40°C shall be not less than 1242 kPa.

3.4.9 500 Hour Pump endurance test. When tested as specified in Appendix 30.6, the pump and fluid shall meet the requirements of Appendix 30.6.8.1 and Table IX.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the contractor is responsible for the performance of all inspection requirements (examinations and tests) as specified herein. Except as otherwise specified in the contract or purchase order, the contractor may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in this specification where such inspections are deemed necessary to ensure supplies and services conform to prescribed requirements.

4.1.1 Responsibility for compliance. All items must meet all requirements of sections 3 and 5. The inspection set forth in this specification shall become a part of the contractor's overall inspection system or quality program. The absence of any inspection requirements in the specification shall not relieve the contractor of the responsibility of ensuring that all products or supplies submitted to the Government for acceptance comply with all requirements of the contract. Sampling inspection, as part of manufacturing operations, is an acceptable practice to ascertain conformance to requirements, however, this does not authorize submission of known defective material, either indicated or actual, nor does it commit the Government to accept defective material.

4.2 Classification of inspections. The inspection requirements specified herein are classified as follows:

a. First article inspection (see 4.4).

b. Quality conformance inspection (see 4.5).

c. Inspection of packaging (see 4.7).

4.3 Toxicity. The contractor shall have the toxicological product formulations and associated information available for review by the contracting activity to evaluate the safety of the material for the proposed use through the submission of the Material Safety Data Sheet detailed in FED-STD-313 (see 3.3 and 6.7).

4.4 First article inspection. First article inspection shall consist of tests for all the requirements of this specification. Failure of any test shall be cause for rejection.

4.5 Quality conformance inspection. Quality conformance inspection shall consist of a sample for tests (see 4.5.3), samples for examination of filled containers (see 4.5.4), and the tests specified in Table VI. Samples shall be labeled completely with information identifying the purpose of the sample, name of product, specification number, lot and batch number, date of sampling and contract number. Unless otherwise specified, sampling of the hydraulic fluid shall be in accordance with MIL-STD-105.

Table VI
Quality Conformance Tests

	Paragraph	
Inspection	Requirement	Test Method
Total acid number	Table II	Table IV
Viscosity	Table II	Table IV
Low temperature stability	Table II	Table IV
Solid particle contamination	3.4.3	4.6.3
Foaming characteristics	3.4.4	Table IV
Water content	Table II	Table IV
Lubricity	Table II	Table IV
Saturation (base oil only)	Table I	30.1

4.5.1 Bulk lot. A bulk lot (batch) is an indefinite quantity of a homogeneous mixture of material offered for acceptance in a single isolated container; or manufactured in a single plant run (not exceeding 24 hours) through the same processing equipment, with no change in ingredient material.

4.5.2 Packaged lot. A packaged lot is an indefinite number of 55-gallon drums or smaller unit containers of identical size and type, offered for acceptance, and filled with a homogeneous mixture of material from one isolated container; or filled with a homogeneous mixture of material manufactured in a single plant run (not exceeding 24 hours) through the same processing equipment, with no change in ingredient materials.

4.5.3 Sample for tests. Samples for tests shall be taken in accordance with ASTM D 4057. This sample shall be subjected to all the applicable quality conformance tests. If the sample for tests fails any of the quality conformance tests, the inspection lot shall be rejected. In addition, a random sample of base oil shall be selected for each lot of the finished fluid and shall be subjected to all the applicable quality conformance tests for base oil.

4.5.4 Sample for examination of filled containers. A random sample of filled unit containers and a sample of shipping containers fully prepared for delivery shall be selected from each lot of fluid in accordance with MIL-STD-105.

4.5.5 Sample for determination of solid particle count. Samples of filled and sealed containers shall be taken at such periodic intervals as to be representative of each day's operation. The number of samples taken each day shall be in accordance with MIL-STD-105, Inspection Level S-3. The sample size and number of determinations shall be as specified in Table V.

Table V
Sample for Particle Contamination

Container	Sample Size (mL)[1]	Number of Determinations Per Sample
1 quart	100	1
1 gallon	200	2
5 gallon	300	3
55 gallon	600	6

[1] Each determination shall be made on 100 mL portions of the sample. Should the particle count on any individual determination be considered excessive, two additional determinations on another sample from the same container may be used. The container shall be thoroughly shaken immediately prior to withdrawing each 100 mL portion for such additional determinations. The arithmetic average of the two closer particle counts shall be considered the particle count of the sample.

4.6 Method of inspection and test.

4.6.1 Inspection. Inspection shall be in accordance with method 9601 of FED-STD-791 and 4.6.5 of this specification.

4.6.2 Tests. The hydraulic fluid properties shall be determined in accordance with the applicable methods specified in Table IV and 4.6.3 and Appendix 30.1 through 30.6. Physical and chemical values specified in Section 3 apply to the average of the determinations made on the samples for those values which fall within any stated repeatability or reproducibility limits of the applicable test method.

Table IV
Test Methods for Basestock and Hydraulic Fluid Properties

Characteristic	Test Method Fed. Test Method Std.	ASTM	Para.
Saturation of Base Oil			30.1
Capillary Gas Chromatography			30.2
Viscosity		D445	
Total acid number		D664	
Lubricity		D4172[1]	
Vapor pressure	3480		
Pour point		D97	
Copper corrosion		D130	
Heat of combustion		D2382, 240 D1405	
Hot manifold ignition	6053		
Low temperature stability, -54°C	3458		
Water		D1744	
Storage stability	3465		
Corrosiveness and oxidation stability	5308		
Swelling of synthetic rubber	3603		
Particle Size			4.6.3
Foaming		D892	
Compatibility			4.6.4
Thermal Stability			30.3
Corrosion Rate Evaluation Procedure			30.4
Bulk Modulus			30.5
Hydraulic Pump Test			30.6

[1] - Condition B

4.6.3 Particle size. Particle size shall be measured by the use of automatic particle counters. Direction in the manual for the respective instrument shall be followed.

4.6.4 Compatibility. Samples of candidate hydraulic fluid in amounts of 20 mL, 100 mL and 180 mL shall be mixed with samples from each of the fluids previously approved under this purchase description. Total volume of each mixture shalll be 200 mL. Mixtures shall be prepared in 250 mL stoppered flasks. The flasks shall be thoroughly agitated and then stored in an oven at 135°C for 2 hours. At the end of this time, any signs of sediment, turbidity or crystallization in any of the mixtures shall constitute failure of the test. The samples shall then be stored at -54°C for a period of 2 hours. Slight turbidity, at this time, that later disappears will be permitted in the samples.

4.6.5 Examination of filled containers. Samples selected in accordance with 4.5.4 shall be examined for compliance with MIL-STD-290 with regard to fill, closure, sealing, leakage, packaging, packing and marking requirements. Any container having one or more defects or under the required fill shall be rejected. If the number of defective or underfilled containers exceeds the acceptance number for the appropriate sampling plan of MIL-STD-105, the samples shall be rejected.

4.7 Inspection of packaging. The packing and marking shall be examined and tested for compliance with the quality assurance provisions of MIL-STD-290 and any other

requirements specified in section 5, herein.

5. PACKAGING

5.1 Packaging and packing. The packing of the of the hydraulic fluid shall be in accordance with the level B or C requirements of MIL-STD-290. Unless otherwise specified, the fluid shall be furnished in 1-quart, 1-gallon, and 5-gallon metal cans conforming to type I of PPP-C-96. All materials used in the construction of the containers shall be such as will not affect or be affected by the contained hydraulic fluid. Just prior to filling, all containers shall be thoroughly cleaned, rinsed with clean, filtered fluid and examined to insure the absolute absence of loose solder, dirt, fibers, lint, metal particles, seaming compound, corrosion products, water or other foreign contaminants. The bottom seam shall show no extruded seaming compound and there shall be no seaming compound on the body immediately adjacent to the side seam. Visible seaming compound, evenly distributed and forming a very fine edge at the point of contact of the seam with the body, shall not be cause for rejection. If a soldered seam is used in the fabrication of the can, residual soldering flux shall not be present on the inside seam of the container.

5.2 Marking. The marking shall be in accordance with MIL-STD-290. Manufacturers/suppliers of products of this product shall provide a hazard warning label in accordance with the Hazard Communication Standard, 29 CFR 1910.1200. The appropriate warning shall convey the specific physical and health hazards including target organ effects of the material. This label shall be affixed to each container.

6. NOTES

(This section contains information of a general or explanatory nature which is helpful, but is not mandatory.)

6.1 Intended use. The hydraulic fluid covered by this specification is intended for use in aircraft systems: automatic pilots, shock absorbers, air compressor gear boxes, brakes, flap-control mechanisms and missile hydraulic servo-controlled systems. It is also intended for use in selected armored vehicles where requirements for vulnerability reduction and crew survivability are so specified, with use applications being in gun recoil mechanisms, turret control systems, braking and steering systems of tracked vehicles, and in other hydraulic systems using synthetic sealing materials.

6.1.1 Storage conditions. Prior to use in the intended equipment, the product may be stored under conditions of covered or uncovered storage in geographic areas ranging in temperature from -54 to +50°C.

6.2 Ordering data.

6.2.1 Acquisition requirements. Acquisition documents should specify the following:

a. Title, number and date of this specification.

b. Issue of DODISS to be cited in the solicitation.

c. Whether a first article sample is required (see 3.1 and 4.4).

d. Quantity and unit package size.

e. Selection of applicable levels of packaging and packing with requirements in detail.

f. Method of sampling and inspection, if other than specified (see 4.2).

g. Test report, if required by acquisition agency.

6.2.2 Purchase Unit. The fluid covered by this specification should be purchased by volume, the unit being a U.S. gallon of 231 cubic inches at 15.6°C.

6.3 First article inspection. When first article inspection is required, the contracting officer should provide specific guidance to offerors concerning the requirements for testing of the preproduction sample of the offered product. Testing should be performed in the contractor's plant, in a Government laboratory, or in a Government approved laboratory. When testing is performed by the contractor or by an independent laboratory, written certification, signed by a responsible officer of the supplier involved, should be furnished stating that the preproduction samples have met all of the requirements of this specification. In addition, a laboratory report should be furnished listing all of the tests performed and the data obtained.

6.3.1 First article test results. Copies of the approved documentation (see 6.3) and a one-gallon sample of the offered product should be sent to the specification preparing activity (see 6.3.2).

6.3.2 Specification preparing activity. Information and instructions regarding first article inspection under this specification may be obtained from the Wright Research and Development Center(WRDC), WRDC/MLSE, Wright-Patterson Air Force Base, OH 45433-6533.

6.3.3 Waiver of first article inspection. First article inspection may be waived at the option of the procuring agency when both of the following conditions have been met:

a. The preproduction sample of the product has passed all of the preproduction inspection requirements within the previous four years.

b. The supplier certifies in writing that the composition of the formulated hydraulic fluid is the same as that of the product which previously met all of the preproduction inspection requirements.

However, neither the approval of the preproduction sample nor the waiving of preproduction inspection requirements should relieve the supplier of the obligation to fulfill all other requirements of this specification.

6.4 Standard samples. Samples of the trimer standard fluid used in the gas chromatographic analysis (see 30.2) of this hydraulic fluid may be obtained from the Wright Research and Development Center, Nonstructural Materials Branch, Non-metallic Material Division, (Symbol: WRDC/MLBT), Wright-Patterson Air Force Base, Ohio 45433-6533.

6.5 Substitutability data. Chlorotrifluoroethylene base hydraulic fluids are not compatible with any other military hydraulic fluids and should not be substituted for any other hydraulic fluids. Hydraulic systems for CTFE base hydraulic fluids are significantly different from hydraulic systems of other military hydraulic

fluids. CTFE base hydraulic fluids cannot be used in hydraulic systems of other military hydraulic fluids and other military hydraulic fluids cannot be used in CTFE base fluid hydraulic systems.

6.6 Subject term (key word) listing.

Chlorofluorocarbons
Chlorotrifluoroethylene
CTFE
Fluid, hydraulic
Hydraulic fluid
Nonflammable hydraulic fluid
NFH

6.7 Material Safety Data Sheets. Contracting officers will identify those activities requiring copies of completed Material Safety Data Sheets prepared in accordance with FED-STD-313. The pertinent Government mailing addresses for submission of data are listed in FED-STD-313.

6.8 Part identification number (PIN). Chlorotrifluoroethylene base hydraulic fluids shall be identified by a PIN consisting of an 'M' prefix and basic specification number, followed by a two-digit number taken from table N indicating the national stock number (NSN) and corresponding container size, as shown in the following example:

Example

```
                          M NNNNN-01
                          :   :    :
Prefix letter -------------   :    :
                              :    :
Specification number ---------     :
                                   :
Dash number ------------------------
```

(National stock numbers have not been established at the date of this specification, so that PIN numbers will not be in effect.)

6.9 International interest. Certain provisions of this specification (see 3.4.4 and 4.6.3) are the subject of international standardization agreement (STANAG 3713 - Determination of Particulate Matter in Aerospace Hydraulic Fluids using a Particulate Size Analyzer). When amendment, revision, or cancellation of this specification is proposed that will modify the international agreement concerned, the preparing activity will take appropriate action through international standardization channels, including departmental standardization offices, to change the agreement or make other appropriate accommodations.

Custodian:

Air Force - 11

Army - ME

Navy - AS

Preparing activity:
Air Force - 11

Review Activities:

Army - AV, MI, AR, EA

Navy - SH

Air Force - 68

DLA - PS

APPENDIX

Test Methods for Evaluating a Nonflammable, Chlorotrifluoroethylene Base Hydraulic Fluid

10. SCOPE

10.1 This appendix covers in detail certain laboratory test methods required to evaluate nonflammable hydraulic fluid. This appendix is a mandatory part of the specification. The information contained herein is intended for compliance.

20. APPLICABLE DOCUMENTS.

20.1 Non-Government documents. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the documents cited in the solicitation (see 6.2).

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARD TEST METHODS

D 1748 - Rust Protection by Metal Preservatives in the Humidity Cabinet.

(Application for copies should be addressed to the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.)

METALS & ALLOYS IN THE UNIFIED NUMBERING SYSTEM

AISI 316 - Stainless Steel
AISI 1010 - Carbon Steel

(Application for copies should be addressed to the Society of Engineers, Inc., 400 Commonwealth Drive, Warrendale, Pennsylvania 15096.)

30. REQUIREMENTS

30.1 Saturation determination method for CTFE (to test for oxidizable materials).

30.1.1 Apparatus.

1. Spectrophotometer (UV quartz cuvettes path length 10 mm) settings.
   slit: 1.0 nm
   Absorbance scale for acetone (blank): 0-2.0
   Absorbance scale for samples and standard: 0-1.0
   scan rate: 50 nm/min
   wavelength scanned: 650 nm to 425 nm

2. Recorder settings.
   5 cm/min
   full scale 100 mv
3. Constant temperature bath set at 25°C ± 1°C.
4. Balance capable of weighing ± 0.0001g.

30.1.2 Materials.

1. 10 mL pipet
2. Test tubes: 25 mm x 200 mm, pyrex
3. Hamilton micro syringe, type 710N
4. Small flask
5. Reagent grade acetone, certified ACS (spectroanalyzed)
6. Double distilled water
7. Potassium permanganate, crystals, reagent grade, ACS
8. Standard CTFE test fluid (see 6.4)

30.2.3 Procedure.

1. Turn on spectrophotometer and bath to warm up.
2. Clean test tubes with distilled water and reagent grade acetone. Dry in oven. Clean micro syringe with acetone. Dry under nitrogen.
3. Prepare a 1% solution of potassium permanganate with the double distilled water. Cover with paraffin film or stopper.
4. In clean test tubes add 1.0 ± 0.05 grams of standard test fluid to two test tubes and 1.0 ± 0.05 grams of sample to another two test tubes. Cover with aluminum foil.
5. Prepare a blank (10 mL of acetone in test tube).
6. Use micro syringe to add 0.06 mL of 1% potassium permanganate to blank, shake and swirl, record time, and quickly transfer test tube to bath set at 25°C ± 1°C.
7. Approximately 15 minutes after blank is in bath, add 10 mL of acetone to standard, shake and swirl, then add 0.06 mL of 1% potassium permanganate solution, swirl, record time, and quickly place standard in bath.
8. After 60 minutes remove first sample (blank), observe color, quickly transfer into clean cuvette and place in spectrophotometer. Check settings of spectrophotometer. Start spectrophotometer and recorder zero the recorder). Scan 650 nm to 425 nm, making sure blank run is set on absorbance scale (0 - 2.0). Measure and record absorbance at 528 nm. Stop at 425 nm, remove sample, clean cuvette and set up for next run. Set absorbance scale (0 - 1.0).
9. Remove the standard from water bath, observe color, quickly transfer to cuvette, and proceed as in step 8. Record absorbance at 528 nm. The other samples will be tested in the same manner.
10. Compare the duplicate standards absorbance. They should not show a difference of greater than .04 absorbance units. If they do, repeat the test.
11. If the absorbance of the sample under test is equal to or greater

than the absorbance of the standard CTFE sample, the test fluid is considered satisfactory and passes. If the absorbance of the test sample of CTFE is lower than the standard, the test shall be considered a failure.

30.2 Capillary gas chromatography method for analysis of chlorotrifluoroethylene (CTFE) fluid.

30.2.1 Scope. This method covers the gas chromatographic analysis of a CTFE fluid.

30.2.2 Summary of method. A candidate CTFE fluid and a standard CTFE trimer fluid are analyzed by a gas chromatographic system. The concentration of the peaks is calculated by taking the percent of the total area contributed by each peak. The total percent of the candidate sample peaks eluting earlier than the standard trimer are reported.

30.2.3 Materials.

1. Hewlett Packard gas chromatograph, Model 5710 or equivalent, adapted for use with capillary columns with a flame ionization detector or equivalent.
2. Fused silica capillary column, length 12 meters, diameter 0.22 mm, methyl silicone, carbowax 20M deactivated stationary phase or equivalent.
3. Chlorotrifluoroethylene trimer standard (see 6.4).
4. Syringe, 5 microliter capacity.
5. Linear recorder, 0 to 1 millivolt.
6. Sample vials.
7. Hewlett Packard autosampler model 7671A (optional).
8. Hewlett Packard 3354 lab automation system or equivalent system for peak integration and calculation.

30.2.4 Procedure. Execute a gas chromatographic run of the trimer standard and the CTFE base fluid by following the gas chromatographic conditions below.

Model:	Hewlett Packard 5710A or equivalent adapted for capillary column use
Column:	
Length:	12m
Diameter:	0.22mm
Liquid phase:	methyl silicone, carbowax 20M deactivated-fused silica
Support:	none
Split ratio:	100 to 1
Auxiliary gas:	He, 40 mL/min
Carrier gas:	He
Carrier gas flow rate:	1 mL/min
Chart speed:	0.66 cm/min
Detector:	FID
Attenuation:	10 x 16

Temperatures
- Injector: 250°C
- Detector: 250°C
- Column: 100-250°C

Temperature program rates: 8°/min
- Initial hold: 8 min
- Final hold: 8 min

30.2.5 Calculations of the CTFE base fluid areas.

1. Add up all the peak areas.
2. Express each peak area as a percent of the total.
3. State that the area percent is the same as the true composition.

$$C_i = \frac{A_i}{n} \times 100$$

C_i = concentration of component i

A_i = area of component i in units of microvolt-seconds

n = total area for entire run, microvolt-seconds

The assumptions used in this calculation are:
- The detector responds quantitatively in the same way to all sample components; that is, all response factors are the same.
- All components are eluted from the column.
- All components are detected and therefore are represented as peaks.

The Hewlett Packard 3354 Lab Automation System carries out this integration.

30.2.5 Results. New CTFE samples with less than 11 percent of the total concentration eluting before the trimer standard as measured (retention time (RT) 2.35 minutes for the above described system) are regarded as acceptable CTFE fluids. Figures 1 and 2 show representative chromatograms.

30.3 Thermal stability test.

30.3.1 Apparatus.

1. Test cell material and configuration is shown in Figure 3.
2. The materials of the 1.27 cm diameter balls are M10 and 52100 steels and naval bronze.
3. Suitable heat source for appropriate temperature with ± 1°C control.

30.3.2 Pre-test procedure.

1. Clean balls and test cell (for duplicate analysis) with suitable solvent in an ultrasonic bath for five minutes.
2. Repeat step (1) two more times with fresh solvent.
3. Dry test cells in an oven at 100°C for one hour.

4. Wipe balls dry with lint-free tissue.
5. Weigh balls to nearest 0.0001g and record. Repeat (4) and (5) until weight change is less than 0.0001g.

30.3.3 Test procedure.

1. Place balls in test cells with M-10 on bottom and 52100 on top.
2. Add 20 $\pm$ 0.1 mL of test fluid in each test cell.
3. Bubble lamp grade nitrogen through fluid for 5 minutes and quickly cap test cells.
4. Weigh test cells and record to nearest 0.1g.
5. Place test cells in heat source for 72 hours at 135°C. Entire 1.9 cm tube section of the test cells should be heated. The safety head must be out of the heated zone.

30.3.4 Post-test procedure.

1. Remove test cells from heat source and allow to cool.
2. Weigh test cells and record to nearest 0.1g.
3. Clean balls and weigh as in pre-test procedure.
4. Determine percent viscosity change at 40°C and total acid number on fluid, per ASTM D445 and ASTM D664, respectively.

30.3.5 Results. Test cell weight loss should be less than 0.5g, or the test results are considered invalid.

30.4 Corrosion Rate Evaluation Procedure for CTFE Hydraulic Fluids.

30.4.1 Scope. The following Corrosion Rate Evaluation Procedure (CREP) is used to determine the relative corrosion protection afforded by corrosion inhibited, nonflammable, chlorotrifluoroethylene hydraulic fluids.

30.4.2 Summary of method. Precleaned, preweighed metal coupons are coated with the test oil formulation and with two standard reference fluids (corrosion inhibited nonflammable fluid and uninhibited basestock). The three test coupons are then suspended together in the 92 $\pm$ 1°C vapor phase of boiling distilled water for a 60 minute residence time. At the end of this exposure cycle the metal coupons are cleaned, dried, and reweighed to five decimal places to determine the metal weight change due to corrosive attack. The three coupons are visually compared. Duplicate samples are run simultaneously in identical apparatus.

30.4.3 Apparatus, materials and reagents. The following are used in this procedure.

1. Reaction kettle: PYREX, 2000 mL capacity, complete with cover having a finely ground flange for a tight seal. The cover has one standard taper 34/45 female joint in the center and three standard taper 24/40 female joints spaced 120 degrees apart with their centers 5.1 centimeters (cm) from the center of the cover.

2. Bushing type reducing adapter, standard taper 34/45 male outer joint, standard taper 24/40 female inner joint.
3. Allihn condenser, water cooled, 40.0 cm jacket length, with a standard taper 24/40 male joint to match the female joint of the standard taper 34/45 to 24/40 bushing type reducing adapter.
4. Ace-thread offset adapter, with a No. 7 ace-thread or equivalent, a threaded nylon bushing, and a buna-N O-ring.
5. Air injection tube, borosilicate glass, 85.0 cm in length, 0.6 cm outside diameter (OD) with one end flared from 0.6 cm to 1.2 cm OD over a distance of 3 cm at one end of the tube.
6. Glass stopper with glass loop. Hollow pennyhead stopper with glass loop fabricated from 0.3 cm OD glass rod; the distance from the base of the stopper to the base of the glass loop is 0.9 cm.
7. Perforated teflon splash suppressor, fabricated from 0.32 cm teflon sheet stock. Splash suppressor disk is 12.7 cm in diameter and perforated with 0.64 diameter holes in seven equally spaced rows, with the center row passing through the diameter.
8. Metal test coupons conforming to AISI-1010. (Corrosion test coupons are fabricated from open-hearth, kilned, low carbon, No. 4 soft temper strip steel. The coupon dimensions are 5.08 x 1.27 x 0.16 cm (2.0 x 0.5 x 0.06 in), with one hole 0.24 cm (0.09 in) in diameter drilled 0.32 cm (0.12 in) from one end of the test coupon and centered across the width. All surfaces and edges of the test coupons are polished to a 10 to 20 microinch finish so that faces are entirely free of pits, scratches or other imperfections. All surface grinding is in the direction parallel to the length of the coupon. The test coupons are then coated with a nonvolatile, water insoluble rust preventative and packaged in a moisture-proof package for shipment or storage. Coupons available from Metaspec, Box 27707, San Antonio, TX 78227.
9. Suspension wire, AMS 5680, stainless steel, 20 gage, cut and formed to the required geometrical configuration.
10. Boiling beads, PYREX, 0.3 cm diameter.
11. Hot plate, electric, Thermolyne Model SP-13115 or equivalent.
12. Air flowmeter, Matheson mass flowmeters or rotometers or equivalent.
13. Metering valve for air flow control, Whitey Model 22rS4 or equivalent.
14. Compressed dry air, Size A cylinder, complete with two stage regulator.
15. Laboratory timer, Model 171 Universal timer or equivalent.
16. Analytical balance, readability 0.1 mg.
17. Desiccator.
18. Wiping tissues.
19. 240 and 320 grit silicon carbide paper.
20. Distilled water.
21. Toluene, reagent grade.
22. Acetone, reagent grade.
23. Methanol, absolute, reagent grade.
24. Dow Corning High Vacuum grease, or equivalent.

25. Coupon draining chamber to provide dust free environment for oil draining cycle. A scaled-down version of the box described in ASTM D1748, Appendix A1.13 or equivalent.
26. Camera, Polaroid type.
27. Die set for numbering coupons.
28. Laboratory aluminum foil.
29. Standard Reference Fluid A = Formulated CTFE (0.05% 3M L1478 and 0.5% barium dinonlynaphthalene sulfonate)
30. Standard Reference Fluid B = CTFE (A02) basestock (See 6.4)

30.4.4 <u>Test specimen preparation</u>.

1. Six metal coupons are required for each test.
2. Identify each coupon using die-cut 0.32 cm (0.12 in) numbers positioned immediately below the suspension hole.
3. Clean the metal coupons by hand polishing with 240 and then 320 grit silicone carbide paper for one minute on each side.
4. Rinse the coupons with water, air dry, and store in a solution comprised of 50 parts toluene and 50 parts absolute methanol until final cleaning.
5. Final cleaning is accomplished by immersing each coupon in boiling toluene, flash drying, and immersing in boiling acetone and flash drying again.
6. Store the test coupons in a desiccator for 30 minutes to equilibrate to ambient temperature, then weigh to five decimal places prior to testing.
7. Maintain specimen cleanliness by handling with forceps.

30.4.5 <u>Test apparatus assembly</u>. Prepare two identical test set-ups so that duplicate test results may be obtained.

1. After carefully cleaning and drying all glassware, place the reaction kettle on the hot plate and add approximately ten boiling beads to the reaction kettle to preclude bumping and splashing of the boiling distilled water.
2. Place the teflon splash suppressor in the reaction kettle so that it is loosely seated against the base of the kettle.
3. Coat the ground glass flange of the reaction kettle with a thin film of silicone grease to prevent condensate leakage and center the cover on the reaction kettle.
4. Fit the center female joint with a standard taper 34/45 to 24/40 reducing type bushing adapter.
5. Insert the male joint of the Allihn condenser into this bushing adapter and insert the male joint of the threaded offset adapter into the female joint at the top of the condenser. Support the condenser as required.
6. Insert the glass air inlet tube through the center of the Allihn condenser and offset adapter and seal with an O-ring in the threaded bushing of the adapter. Position the air inlet tube so that the flared end is 5.1 cm (2.0 in) above the base of the kettle.

7. Place the glass stoppers with the glass hooks in the remaining three female joints of the cover.
8. Form the coupon suspension hooks, shaped from the AMS 5680 20-gage stainless steel wire, so that the bottom edge of the test coupon is 11 cm (4.3 in) from the base of the kettle.
9. Prepare the regulated dry air source using using the micrometer valve for flow control and the calibrated flow meter for air flow measurement.

30.4.6 Test procedure.

1. After assembling the test apparatus, remove the reaction kettle and cover from the hot plate, leaving the condenser and air flow assembly attached to the support stand.
2. Preheat the hot plates and allow to equilibrate at the highest setting.
3. Start the water flow through the condenser.
4. Add 100 mL of distilled water to the reaction kettle and re-assemble the apparatus on the equilibrated hot plate.
5. Establish an air flow rate of 500 standard cubic centimeters per minute (SCCM) to the reaction kettle before the water starts to boil. This high air flow keeps the temperature around the coupons at approximately 92° C.
6. Allow the system to equilibrate for 60 minutes before the test specimens are introduced.
7. Maintain test temperature of the kettle by loosely wrapping the kettle and glassware below the condenser with aluminum foil to avoid cooling by drafts.
8. Immerse two of the previously prepared test coupons in the each of the three fluids (test fluid, standard reference fluid A, standard reference fluid B) for five minutes.
9. Remove the coupons and suspend in a vertical position in a dust free environment for 15 minutes.
10. Remove the excess oil at the bottom edge of the test coupons by light quick dabbing with a wiper.
11. Suspend the test coupons (one coated with each fluid in each reaction kettle) by the wire hooks from the glass stoppers and insert in the reaction kettle for 60 minutes.
12. Remove the test coupons from the reaction kettle at the end of the test and photograph before cleaning.
13. Numerically rate the appearance of the coupon of the tested fluid, comparing it to the coupons that were immersed in the standard reference fluids. The coupons corresponding to Standard Reference Fluid A (with corrosion inhibitor) and Standard Reference Fluid B (basestock) are rated 10 and 0, respectively. Visual ratings are based on a linear interpolation of the sample coupon compared to the two reference coupons.
14. Remove all loose material from the coupons by wiping with a paper tissue or laboratory wipe.
15. Immerse the coupons in boiling toluene for five minutes, and in boiling acetone for five minutes.

17. Flash dry the coupons and place in a desiccator to equilibrate to ambient temperature.
18. After 30 minutes, weigh the test coupons to five decimal places, and calculate the weight change.

30.4.7 <u>Results</u>. A weight change of greater than 20 mg is considered a failure. A visual rating of less than 8 is considered a failure.

30.5 <u>Bulk modulus</u>.

30.5.1 <u>Apparatus</u>. The bulk modulus of the hydraulic fluid shall be determined using a calibrated precision capillary pycnometer of the type shown in Figure 4 (modified 21 T 50 Jersuson or equivalent). A suitable pressure vessel and auxiliary equipment for this determination are shown in Figures 5 and 6.

30.5.2 <u>Procedure</u>. The pycnometer volume to capillary diameter ratio shall be chosen to provide a precision of measurement for liquid density of $\pm$ 2 parts in 10,000. The pycnometer shall be charged with candidate fluid to the top of the capillary at 40° C constant-temperature bath, allow equilibrium to be reached, and take volume reading at atmospheric pressure. (Since the precision of the unit depends on visual readings, care must be taken to avoid errors due to parallax and distortion in the pressure vessel window and the walls of the constant-temperature bath.) Increase nitrogen pressure to a new level, and after a 1-hour soak, take a third reading. For any pressure range, the secant bulk modulus is defined by the following equation:

$$\text{Bulk modulus} = \frac{V\ (\text{delta } P)}{V + (\text{delta } V_g)}$$

Where:

V is the original volume of the fluid
delta V is the observed volume change due to P increase in pressure
delta P is the pressure change between the two measurements in kPa
delta V_g is the correction factor

The correction factor (delta V_g) considers the bulk modulus of glass in determining the true volume of the pycnometers at pressures above atmospheric. The bulk modulus of pyrex glass is 3.28 × [illegible] kPa (4.77 × 10^{6} psig).

Therefore:

$$\text{delta } V_g = \frac{V\ (\text{delta } P)}{3.28 \times [illegible]}$$

30.6 **Test for performance of hydraulic fluid in a high performance hydraulic pump.**

30.6.1 Scope. This method is used for determining the performance of hydraulic fluid in an aircraft hydraulic pump. Evaluation is based on the ability of the hydraulic pump to maintain performance throughout the cycle, composite wear of pump parts, measured by way of case drain flow, and the physical and chemical condition of the hydraulic fluid monitored throughout the test.

30.6.2 Method summary. The test involves the cyclic operation of a hydraulic pump in a closed loop test stand, for a total of 500 hours. Prior to the test, the pump is prepared as described herein.

30.6.3 Sample size. A minimum of 15 Liters (4 Gallons) of test fluid is required.

30.6.4 Test pump. "VICKERS" inline type, pressure compensated pump model PV3-075-15 is used for this evaluation.

30.6.5 Test apparatus.

30.6.5.1 Test stand. Figure 7 shows the schematic diagram of the test stand. The test stand consists of a drive motor, throttling valve, heat exchanger, reservoir, filters, pressure relief valve, check valve, hand pump and instrumentation. The throttling valve serves as a flow control device. Working volume of the fluid in the test loop should be between 3 Liters (0.8 Gallon) and 3.8 Liters (1.0 Gallon). The reservoir is not in the test loop, but provides makeup fluid only when fluid samples are taken or leakage occurs. All lines, fittings and other metallic components shall be made of stainless steel (such as AISI 316) or materials compatible with chlorotrifluoroethylene (CTFE) base hydraulic fluids. Table VIII shows the description of components successfully used by the U.S. Air Force for CTFE pump tests. Information in Table VIII is provided for reference only.

Table VIII

Components Used on WRDC/MLBT Pump Test Stands

No.	Description	Manufacturer	Part Number
1	Pressure transducer	Sensotec	Model A & Model Z
2	Hand hydraulic pump	Teledyne Republic	3-1158-18 & 914-8028
3	Valves	Hoke	2200 Series
4	Pressure relief valve	Nupro	SS-4R3A5
5	Check valve	Nupro	SS-CHS8-1
6	Flow meter	Flow Technology (FTI)	FT-12AX20-LB
7	Flow filter	Aircraft Porous Media, PALL	AD-3258-12HM5, M8815/1-12
8	Filter element	Aircraft Porous Media, PALL	AC7031F1297Y3 (5 microns)
8	Pressure gauge	McDaniel Controls, Inc.	Code F, P SS 0-1000 psi
10	Throttling valve	McGraw Edison Company	Model 5061
11	Throttling valve	General Controls Company	7605MDSRJ

30.6.5.2 Instrumentation.

30.6.5.2.1 Temperature measurements. Provisions shall be made for thermocouple installation as listed below. Total system accuracy shall be calibrated to $\pm$ 1° C to measure test fluid temperature. Thermocouples shall be shielded and unless specified, shall be immersed to the midstream and located as close to the components as practical.

Variable	Location
Pump inlet temperature	In pump inlet line
Pump outlet temperature	In pump outlet line
Throttling valve (T/V) outlet temperature.	In T/V outlet line
Case drain temperature	In case drain line

30.6.5.2.2 Flow measurements. Provisions shall be made for fluid volume flow measurements with a resolution of $\pm$ 0.4 lpm ($\pm$ 0.1 gpm). Fluid flow in the pump outlet and case drain line shall be measured.

30.6.5.2.3 Pressure measurements. Provisions shall be made for fluid pressure measurements with a resolution of $\pm$ 6.9 kPa ($\pm$ 1 psi). Pressure sensors shall be installed to monitor the following:

a. Pump inlet pressure
b. Pump outlet pressure
c. Case drain pressure

d. Main filter pressure drop
e. Case drain filter pressure drop

30.6.5.2.4 Pump speed. Provision shall be made for pump shaft speed measurement with a resolution of $\pm$ 10 rpm.

30.6.5.2.5 Torque Measurements. Provision shall be made to measure torque on the pump shaft, with a resolution of $\pm$ 0.6 N-m ($\pm$ 5 in-lb).

30.6.6 Materials.

30.6.6.1 CAUTION. SOME MATERIALS ARE TOXIC AND HAZARDOUS. The chemical material listed in this section must be handled carefully. Federal Test Method 10000T, Material Handling Safety Precautions, is a reference which lists all toxic and hazardous materials cited in FTMS 791. The synonyms, life hazard, flammability, handling and storage precautions, emergency treatment and measures, and spill practices of each chemical are explained.

30.6.6.2 Cleaning solvent. Heptane may be used for cleaning parts as described herein. Chlorinated solvents must not be used for cleaning.

30.6.7 Procedure.

30.6.7.1 Preparation for test.

30.6.7.1.1 Pump preparation. A new pump shall be used for every test. Preservative fluid from the pump casing shall be drained. Pump shall be completely disassembled, cleaned thoroughly with heptane, blow dried with nitrogen and placed in an oven at 66°C for 30 minutes. All elastomeric seals shall be replaced with "VITON" seals. Pump shall be assembled and the casing filled with the test fluid. During disassembly and reassembly, care must be taken to install the pistons in their original cylinder bores.

30.6.7.1.2 Test stand preparation. Test stand shall be completely disassembled and thoroughly cleaned by spraying heptane on all the parts. All fittings, lines and other components shall be cleaned to remove any residual metal and fluids from previous tests. If necessary, a piece of clean cloth (cheese cloth or similar) shall be run through the tubings for cleaning. Parts may be blow dried with nitrogen and placed in an oven at 66°C for 30 minutes to remove any solvent left on the parts. All elastomeric seals shall be replaced with new "VITON" Seals. Test pump, as prepared in 30.6.7.1.1 shall be mounted on the drive motor/torque sensor assembly. Splines on the pump shaft shall be adequately lubricated with a fretting-corrosion resistant grease. Test stand shall be filled with 9-11 liters (2.5-3 gallons) of the test fluid. Any air in the system shall be removed to avoid cavitation damage to the components. Air bleeding procedure may vary from one test stand to another. A typical bleeding procedure used by the U.S. Air Force in its pump tests is listed in 30.6.7.1.3.

30.6.7.1.3 Bleeding procedure.

1. Using the hand pump, the hydraulic test fluid is slowly pumped into the reservoir. At this time, the valve in the line connecting the reservoir to the test loop is left closed (see figure 7).
2. After the correct amount of test fluid is pumped into the system, the hand valve is opened to allow the fluid to get into the test loop.
3. Approximately 5 psig of nitrogen pressure is then applied to the system.
4. Next, after applying the pressure, two or three fittings are chosen to be bleed ports. Fittings higher in elevation relative to the rest of the system are usually chosen since trapped air tends to seek the highest points in the system. These fittings are loosened until the trapped air ceases to esxcape and the fluid begins seeping around the fitting.

5. At this time, pump/motor shaft is turned manually to circulate the fluid in the test loop and to migrate the air to the bleed ports. Because air bubbles are slow rising, the system is left untouched for 15-20 minutes. The system is bled at this time allowing for the trapped air at the bleed ports to be released.
6. Step (5) is repeated 3-4 times.
7. System pressure is increased to 15 psig and step (5) is repeated 3-4 times.
8. Pressure is increased to 50-55 psig and step (5) is repeated 3-4 times.
9. The pump shaft is rotated at about 500 rpm for 5-10 seconds. Bleeding is done after 20-30 minutes. This procedure is repeated 3-4 times.
10. Step (9) is repeated except the motor speed is increased to 5000 rpm and maintained for 10-15 seconds.
11. The pump/motor shaft is rotated at 5000 rpm for 2-3 throttling valve cycles (2-3 minutes). The system is bled after 20-30 minutes. This step is repeated 3-4 times.
12. The pressure is dropped to 5 psig. System is bled after 20-25 minutes.
13. System pressure is increased back to 50-55 psig and the pump/motor shaft is rotated at 5000 rpm. The system is monitored for sound. If there is still trapped air in the system, a peculiar rough noise is heard. This noise is similar to cavitation noise. If air is still present, steps k,l,m must be repeated until the system is running smoothly and no air escapes the bleed ports.

NOTE: The bleeding procedure may take a lengthy 2 days or a brief 8 hours to obtain satisfactory results.

30.6.7.2 Test run.

30.6.7.2.1 Test duration. Duration of the test will be 500 hours.

30.6.7.2.2 Test cycle. Pump will be run at maximum flow rate for 60 seconds and then at minimum flow rate for 60 seconds. This alternate cycling shall be maintained throughout the test duration. Hereafter, the maximum flow cycle is referred to as TVO (throttling valve open) and the minimum flow rate cycle is referred to as TVC (throttling valve closed).

30.6.7.2.3 Test parameters. The following parameters shall be maintained during the test.

Test Parameter	Maximum	Minimum
Pump Speed (rpm)	5100	5000
Main Flow Rate (TVO) lpm(gpm)	49 (13)	44 (11.5)
Main Flow Rate (TVC) lpm(gpm)	15 (4)	11 (3)
Pump Inlet Pressure kPag(psig)	481 (70)	345 (50)
Pump Outlet Pressure kPag(psig)	21030 (3050)	19651 (2850)
Bypass Fluid Temperature °C	124	116
Fluid Temperature at any location, °C	124	

30.6.7.2.4 Fluid Samples. A 40 to 60 mL fluid sample shall be taken from the test stand at the following intervals.

Sample No.	Test Hours
1	4 - 6
2	20 - 30
3	45 - 50
4	90 - 110
5	140 - 160
6	190 - 210
7	240 - 260
8	290 - 310
9	340 - 360
10	390 - 410
11	440 - 460
12	490 - 500

30.6.7.2.5 Data recording. Test parameters shall be recorded every 15 - 25 hour interval. A typical data sheet is shown in Figure 8.

30.6.7.2.6 Mechanical problems. Problems experienced in the test stand during the testing may be corrected. No modifications to the pump may be made during a test.

30.6.8 Evaluation criteria.

30.6.8.1 Failure criteria. The fluid shall be considered to have failed the test if any of the following criterion is met.

1. Pump fails catastrophically.
2. Pump fails to maintain pressure and flow.
3. Case drain (pump bypass) flow increases to twice its value at the start of test.
4. Fluid temperature rise in the pump is more than 11°C.
5. A fluid sample fails the criteria listed in Table IX

Table IX

Fluid Sample Failure Criteria

Determination	Limit
Fluid appearance	Cloudy when sampled (failure)
Kinematic viscosity change, % cSt at 40°C	10 max
Total acid number mg KOH/g	1.5 max
Capillary gas chromatography, % new peaks	2 max
Water, ppm	500 max
Metal analysis	Report

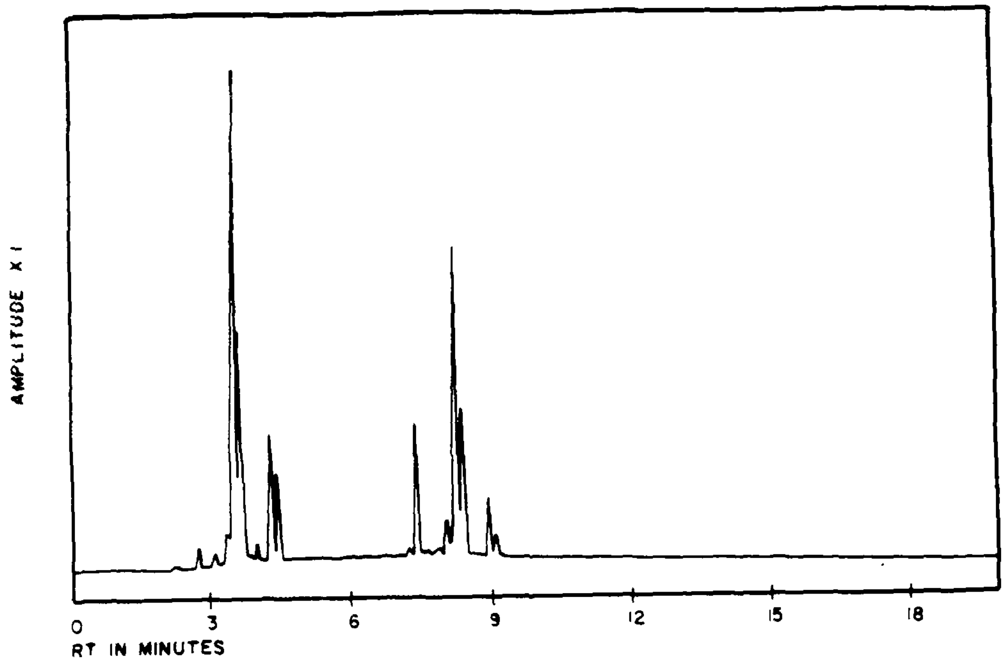

FIGURE I. Capillary GC of CTFE base fluid.

X-4931

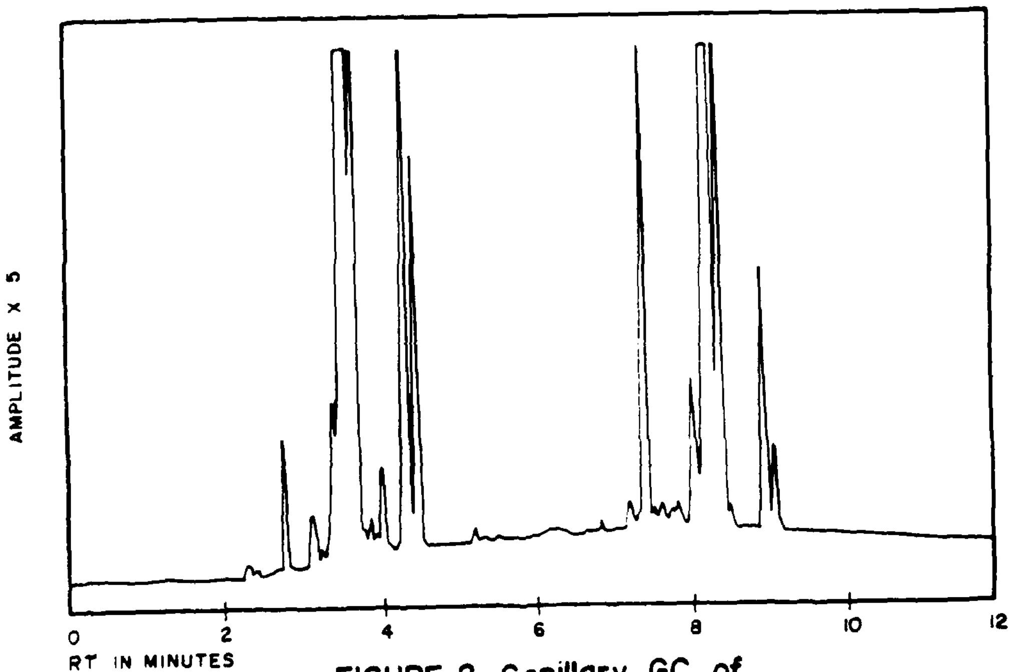

FIGURE 2. Capillary GC of CTFE base fluid.

X-4932

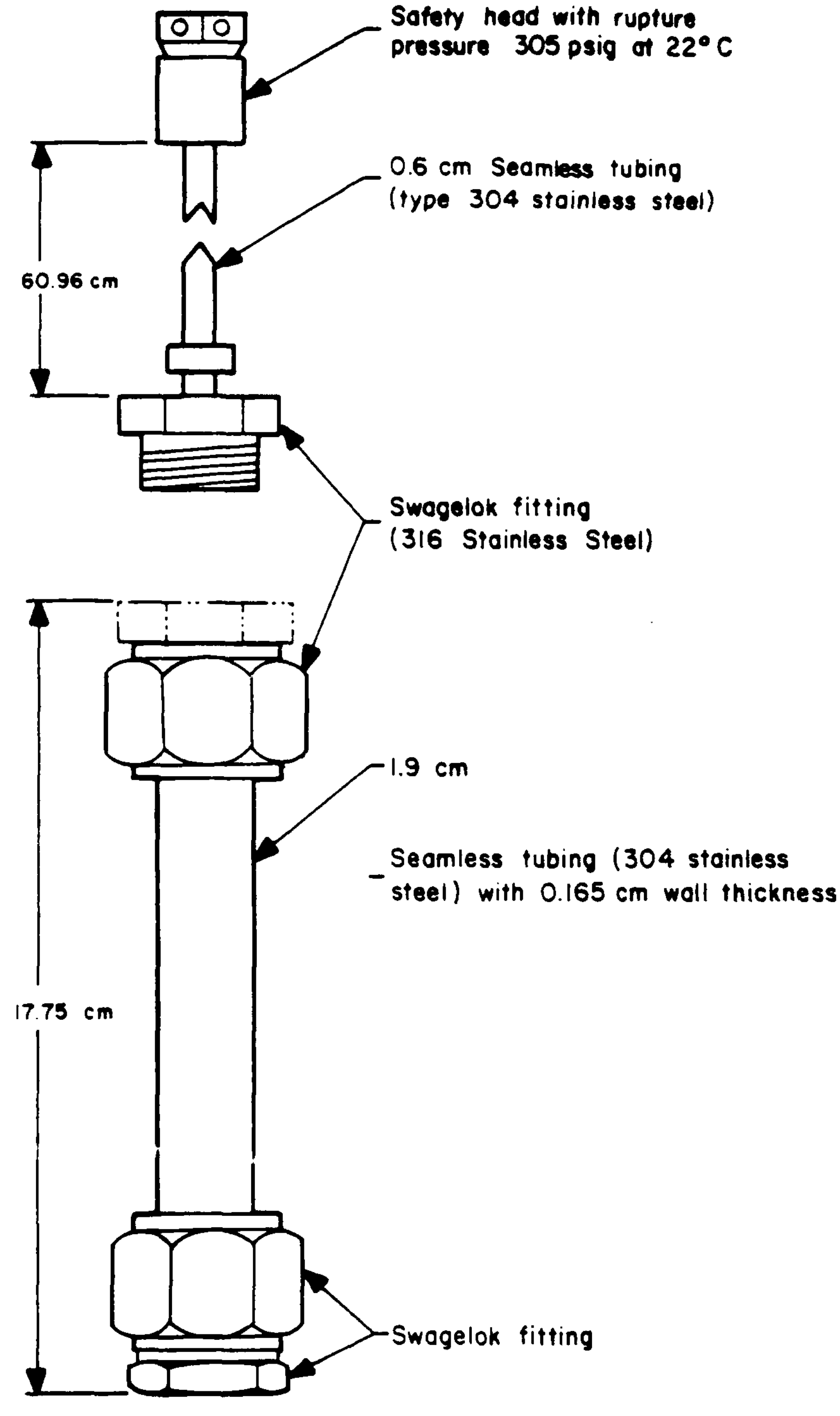

FIGURE 3. Thermal stability test cell.

X-4933

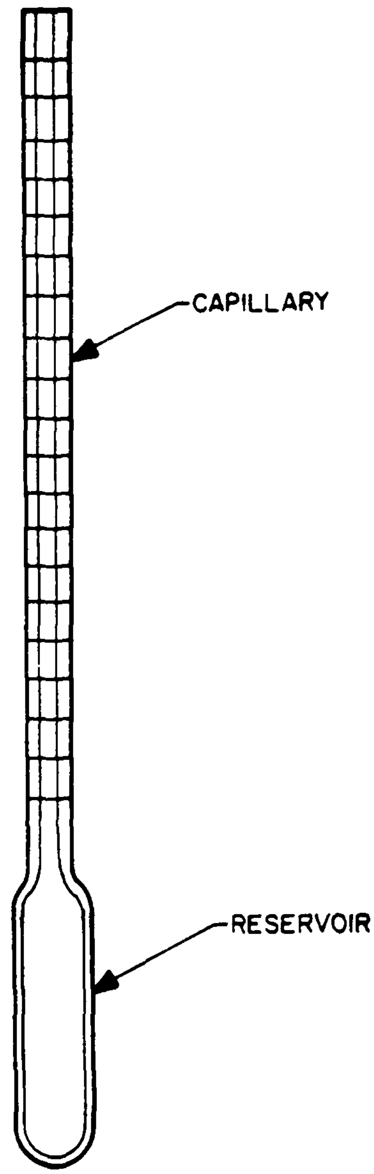

FIGURE 4. Precision capillary pycnometer.

X-4934

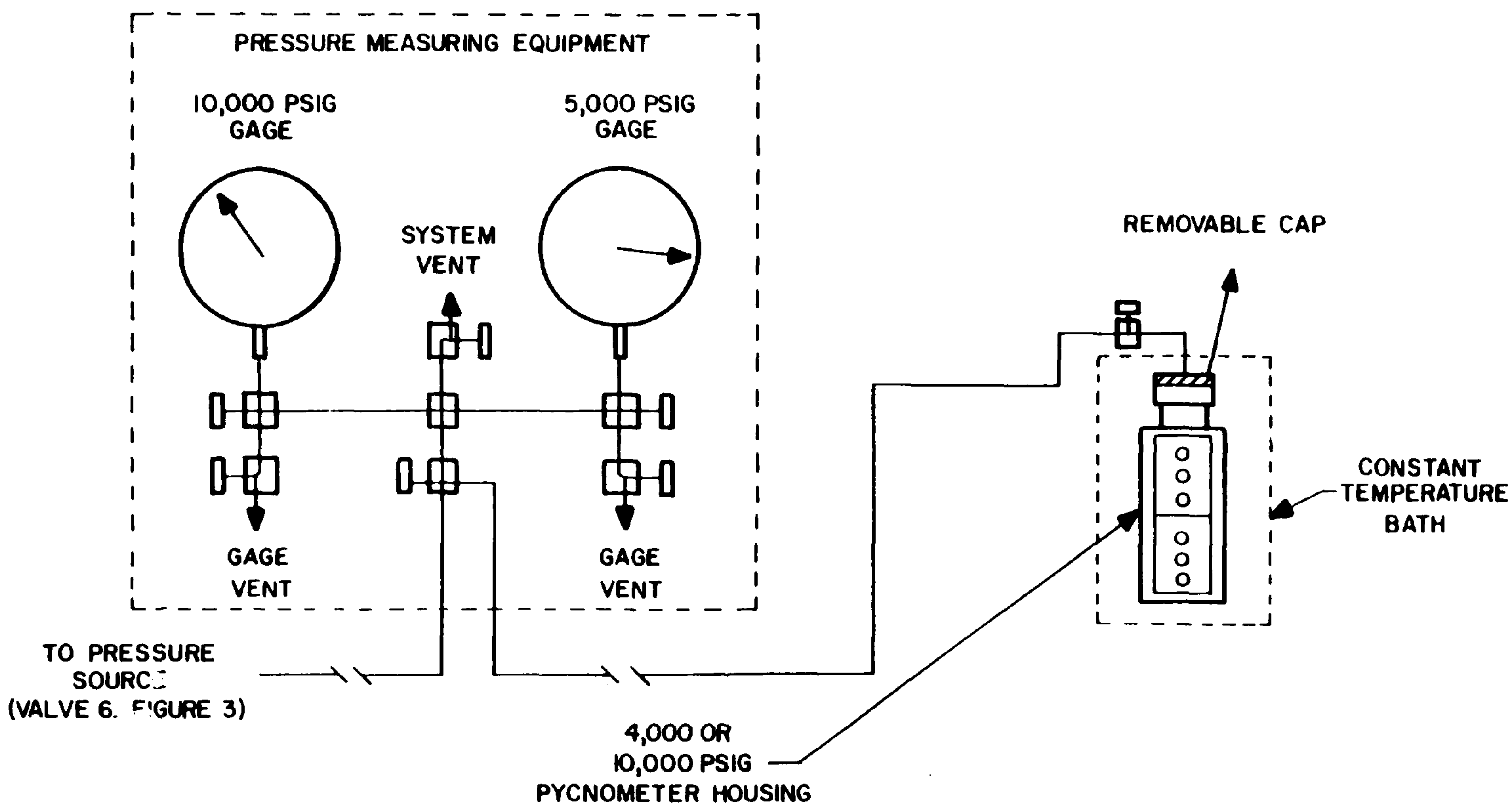

FIGURE 5. Diagram of bulk modulus equipment.

X-4935

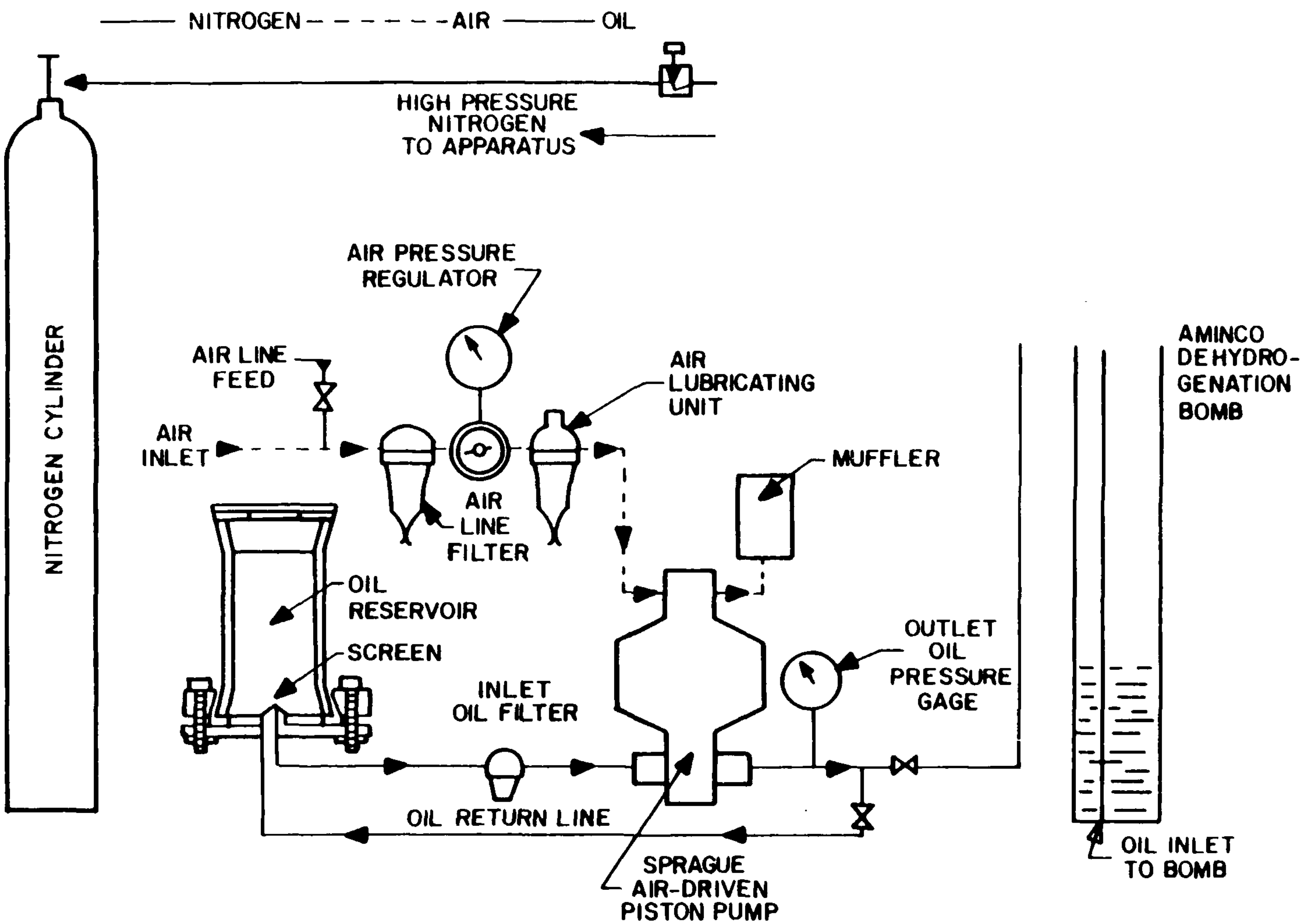

FIGURE 6 Auxillary equipment.

X-4936

FIGURE 8

Pump Test Fluid Sample Data Sheet (Sample)

Sample Number	Test Hours	Fluid Appearance	% Kinematic (a) Viscosity Change @ 40C	TAN (b) Change mg KOH/g	Capillary Gas (a) Chromatography New Peaks, %	Water ppm (c)	Metal Analysis	Infrared (d) Spectro-Photometry
Baseline from fluid container	-	Clear, amber	-		-			
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								

a. Provides an indication of inadvertent system contamination.

b. Must be performed soon after the sample is taken; no later than twelve hours.

c. Provides an indication of stand heat exchanger leaks.

d. Optional; recommended for system and/or fluid diagnostics.

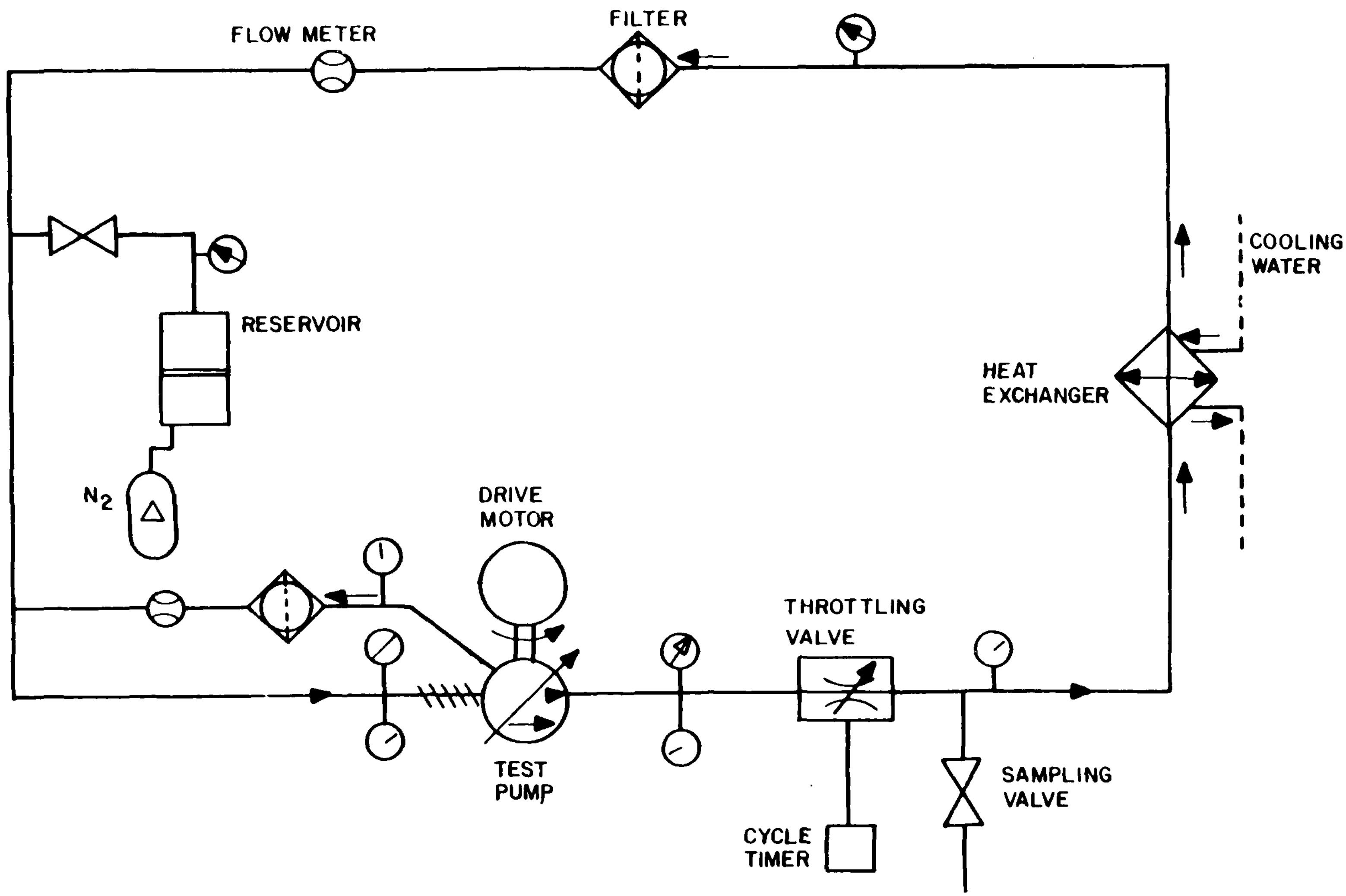

FIGURE 7. Schematic of Aircraft Hydraulic Pump Test Stand.

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